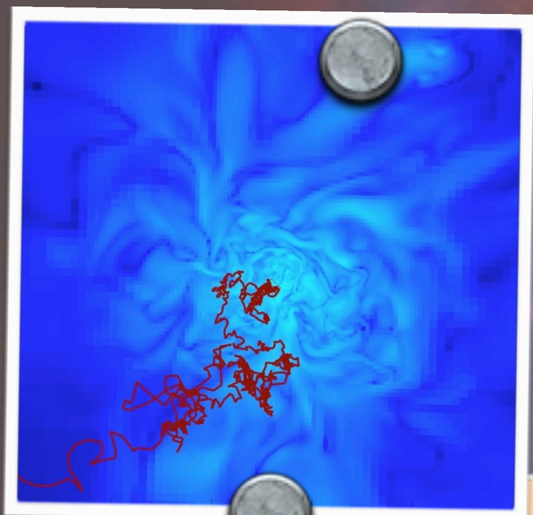
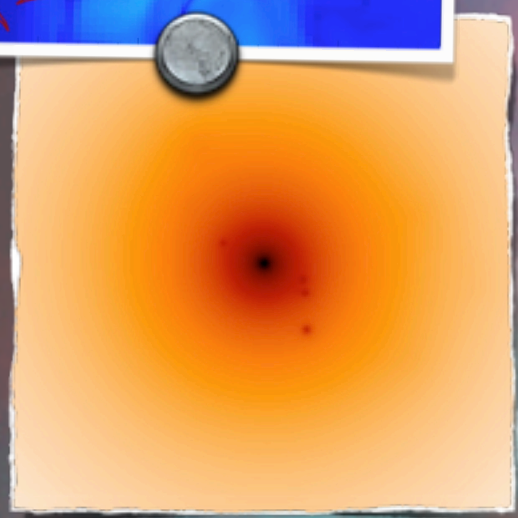
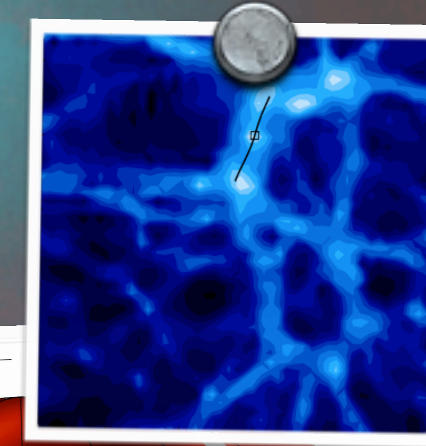
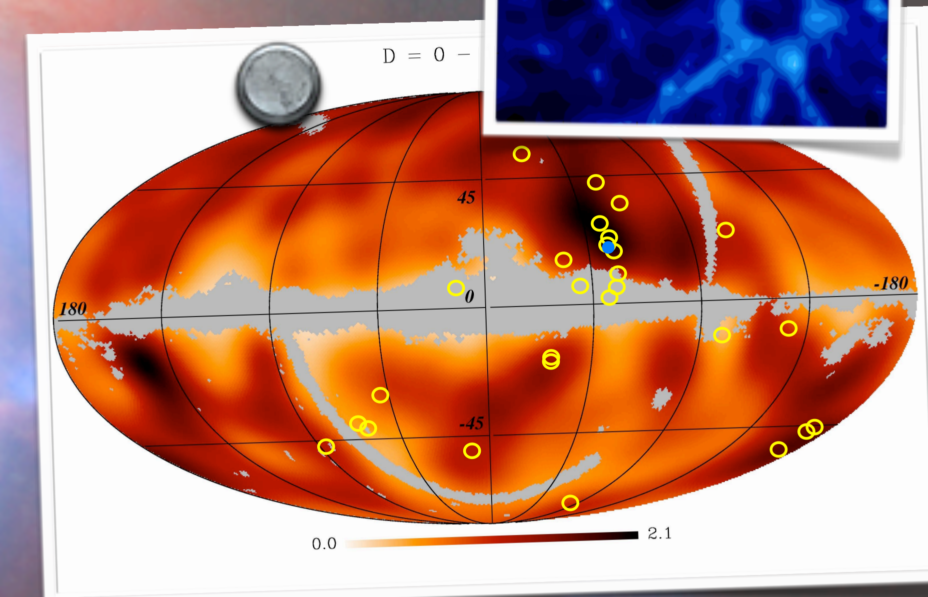
From the magnetized Universe to neutrinos:

a life of an ultrahigh energy cosmic ray



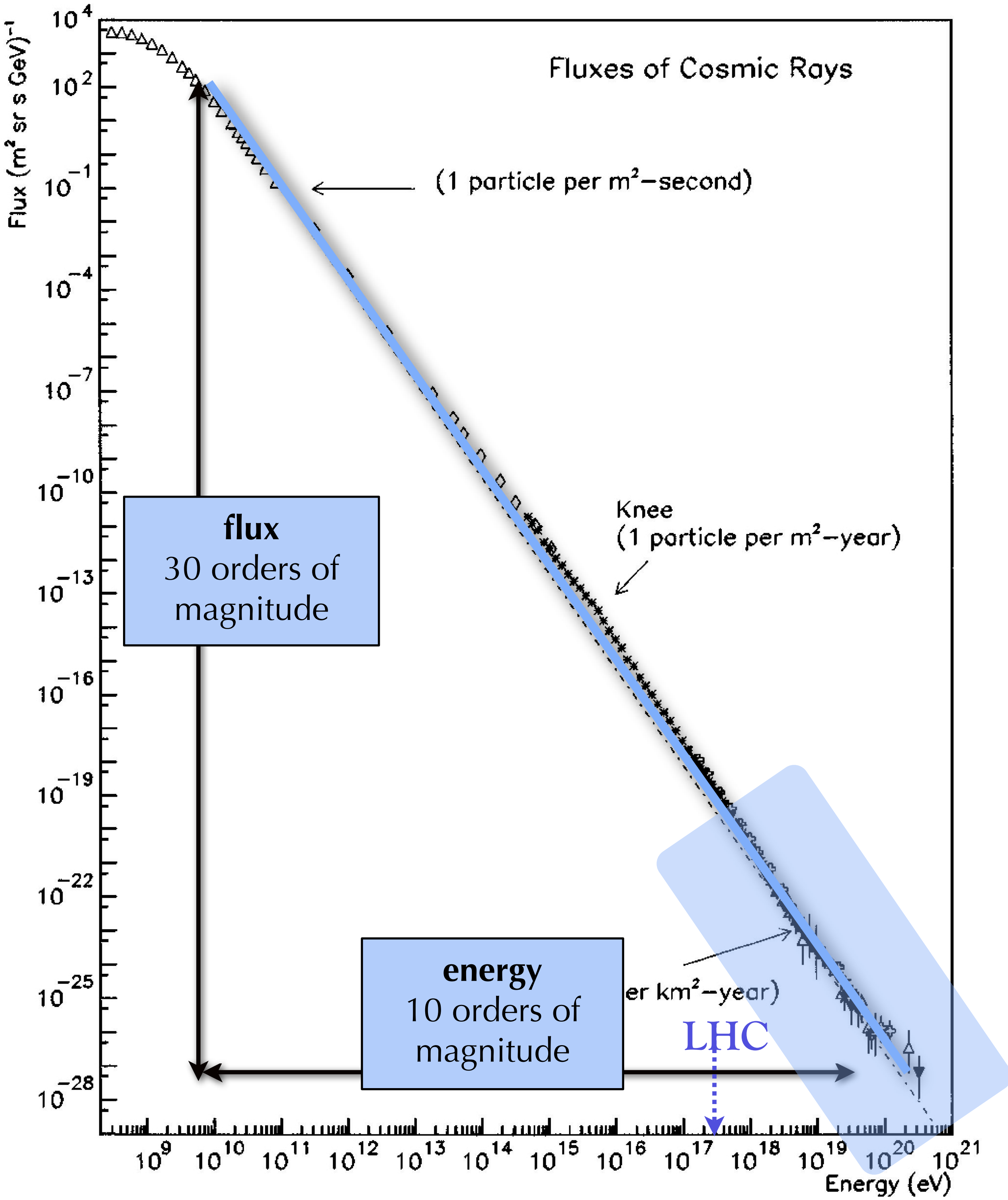






Kumiko Kotera, *Institut d'Astrophysique de Paris*

The puzzle of ultrahigh energy cosmic rays



Why do we care about cosmic-rays?

Energies that cannot be reproduced on Earth!
Universe thru different eyes

The puzzle:

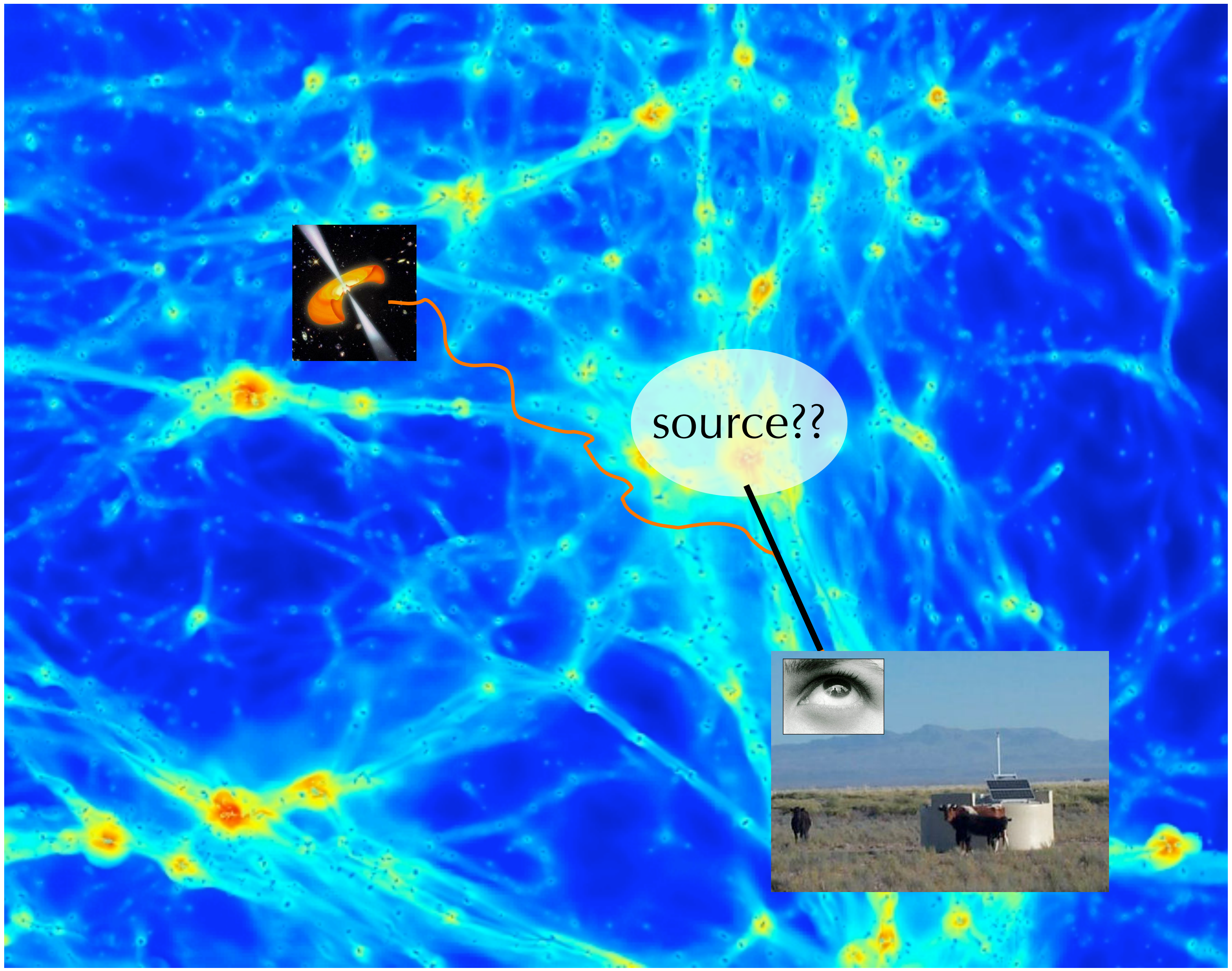
What source(s)?
What physical mechanism(s)?

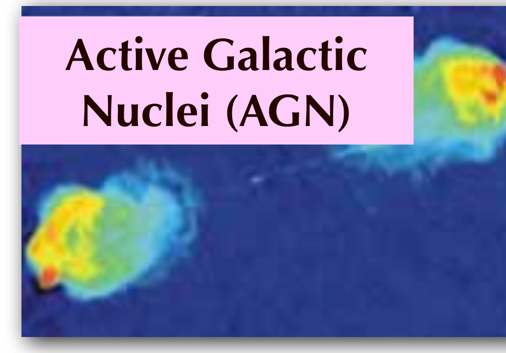
Why is it so difficult?

- detection issues
- Particle Physics issues
- astrophysical issues

Astrophysical issues

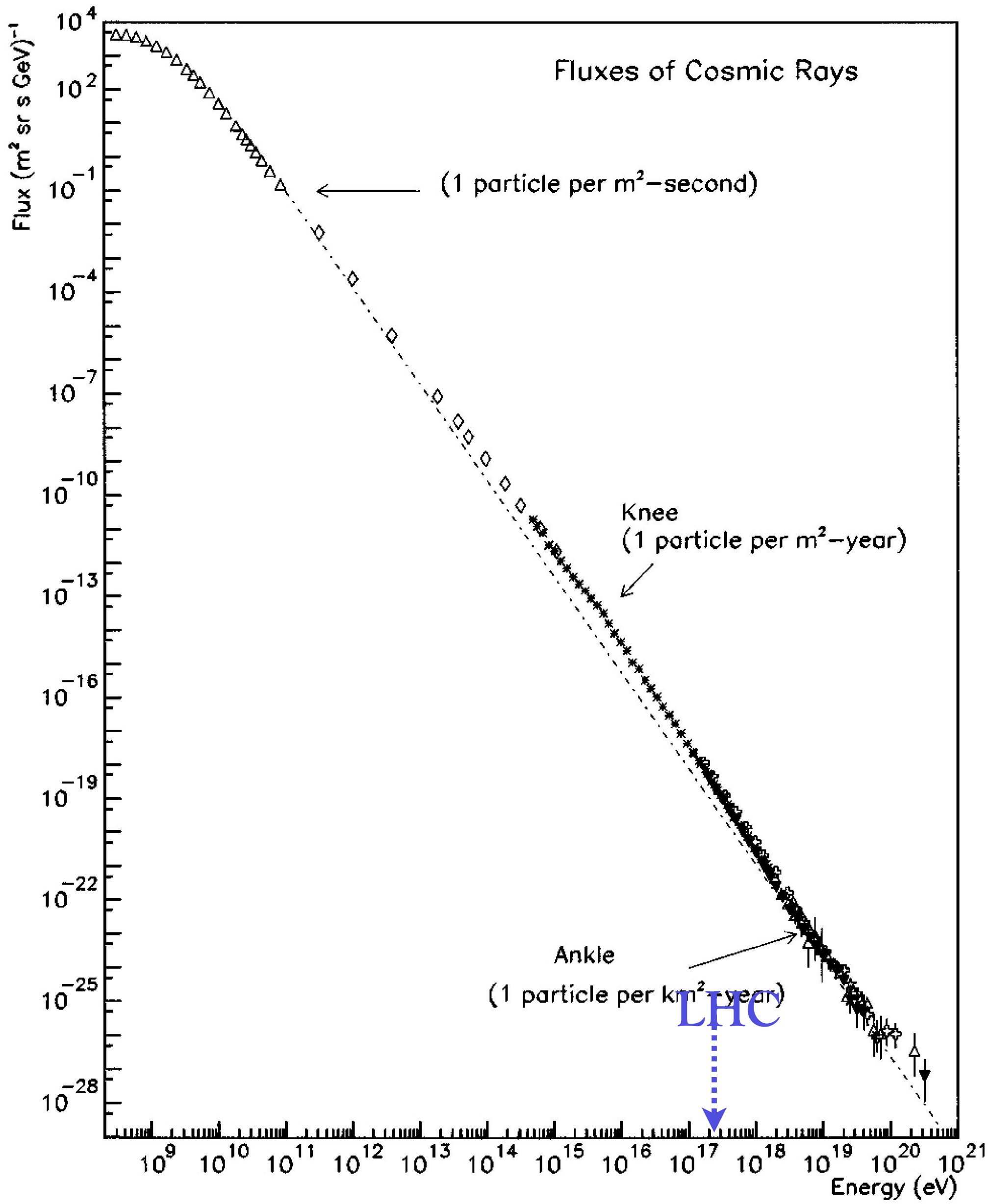
UHECRs are charged particles *and* the Universe is magnetized

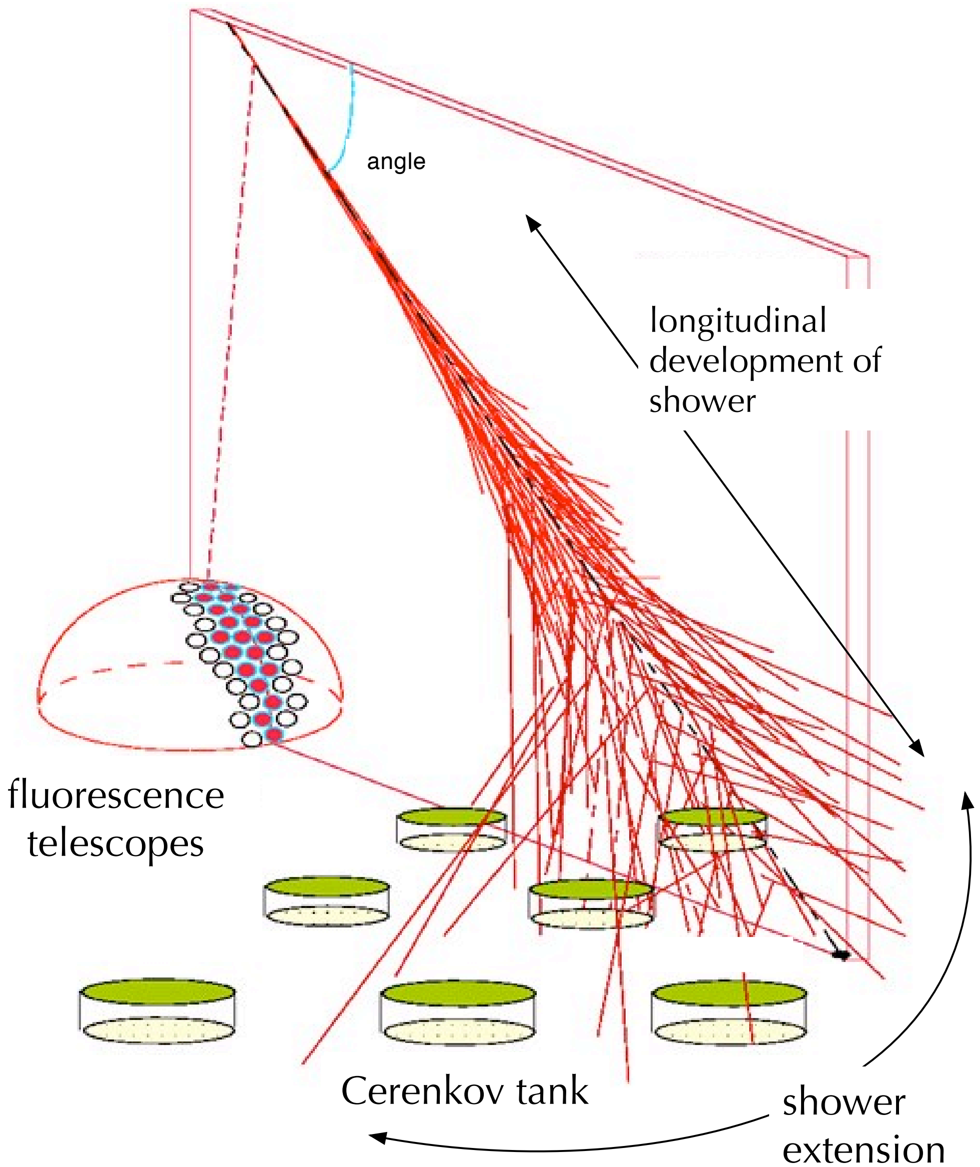




Physics of powerful astrophysical objects is not known in detail

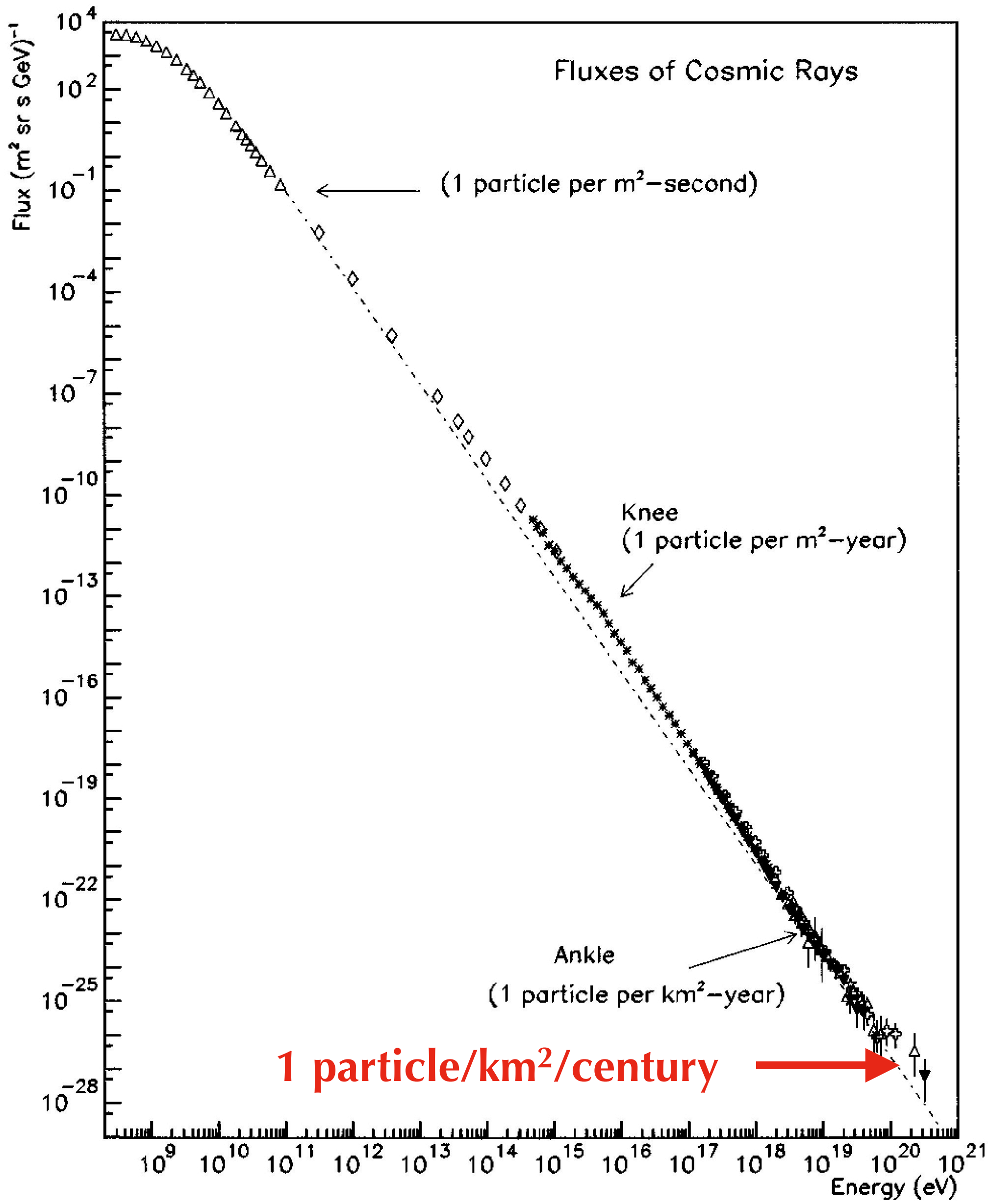
Particle Physics issues





ultrahigh energies that cannot be reproduced on Earth ($E \sim 2 \text{x} 10^{20}$ eV)
shower development (hadronic interactions) still unknown

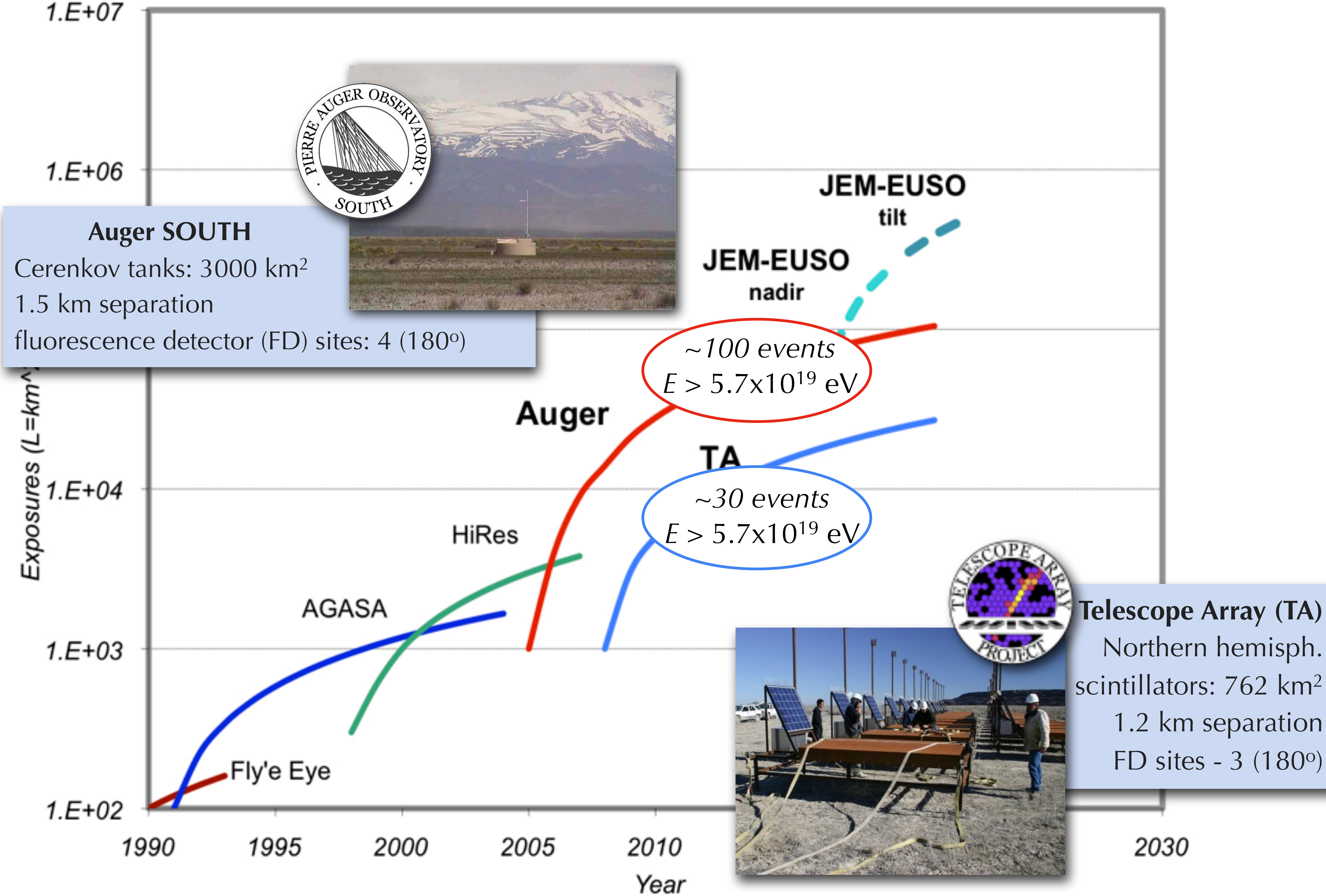
Detection issues



low flux!

necessity to build larger and larger observatories

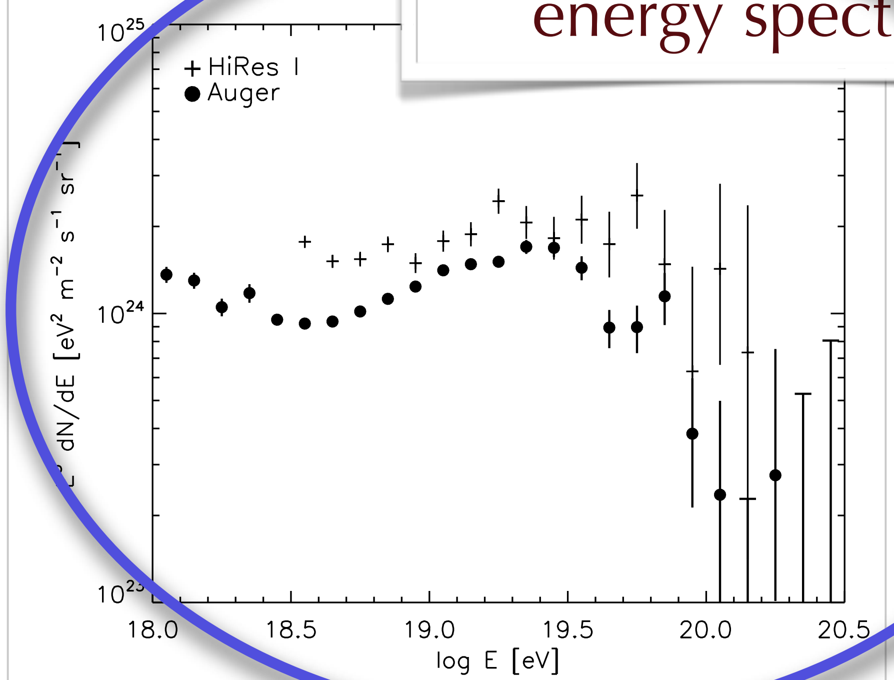
Since 1990 in ultrahigh energy cosmic rays



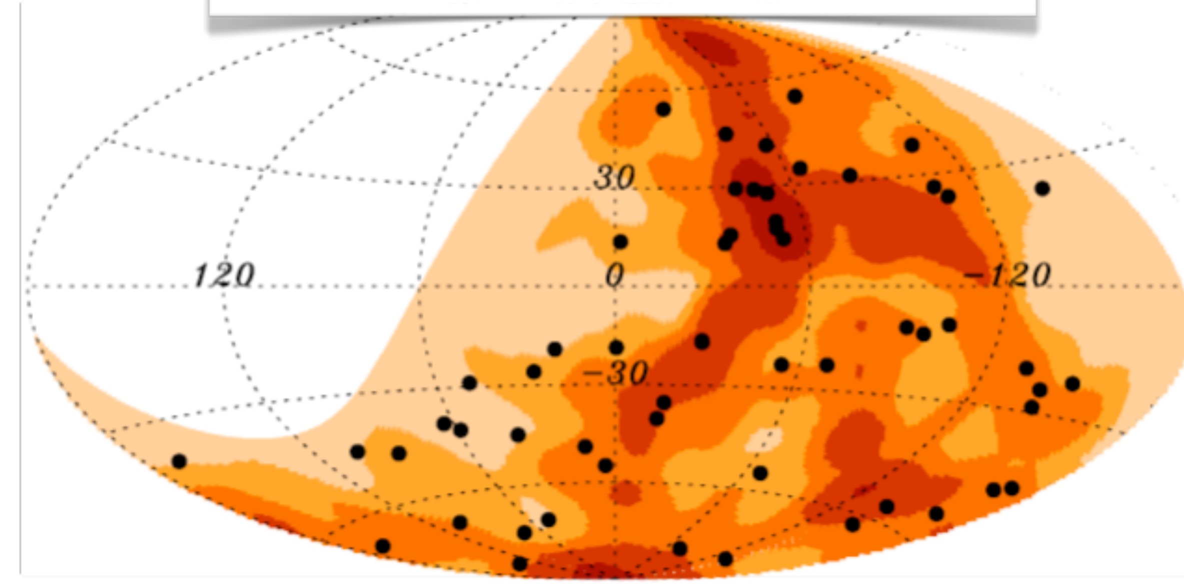
K.K. & Olinto 11

What observational information do we have?

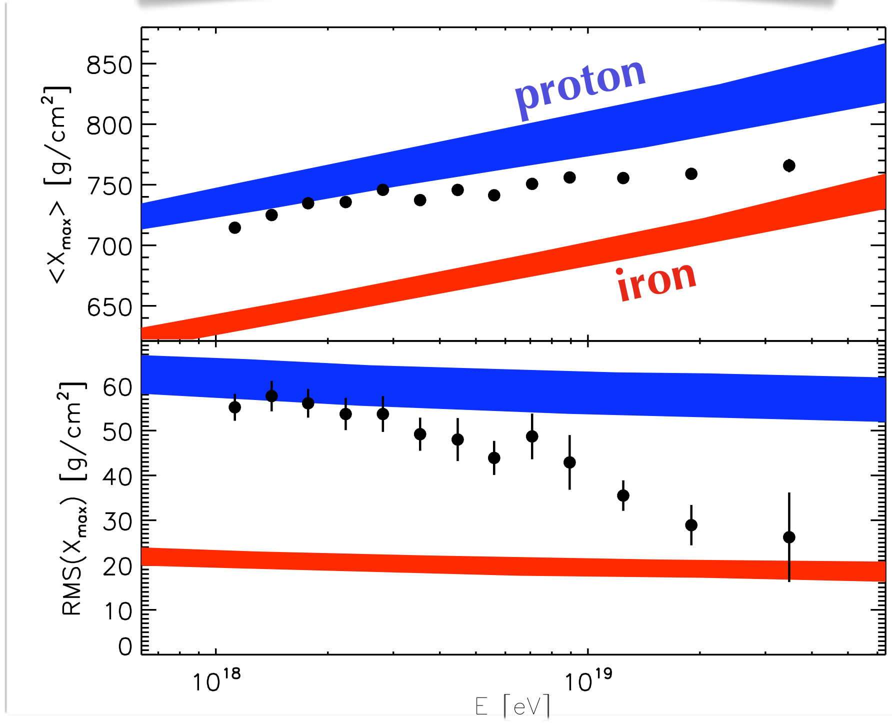
energy spectrum



arrival directions in the sky

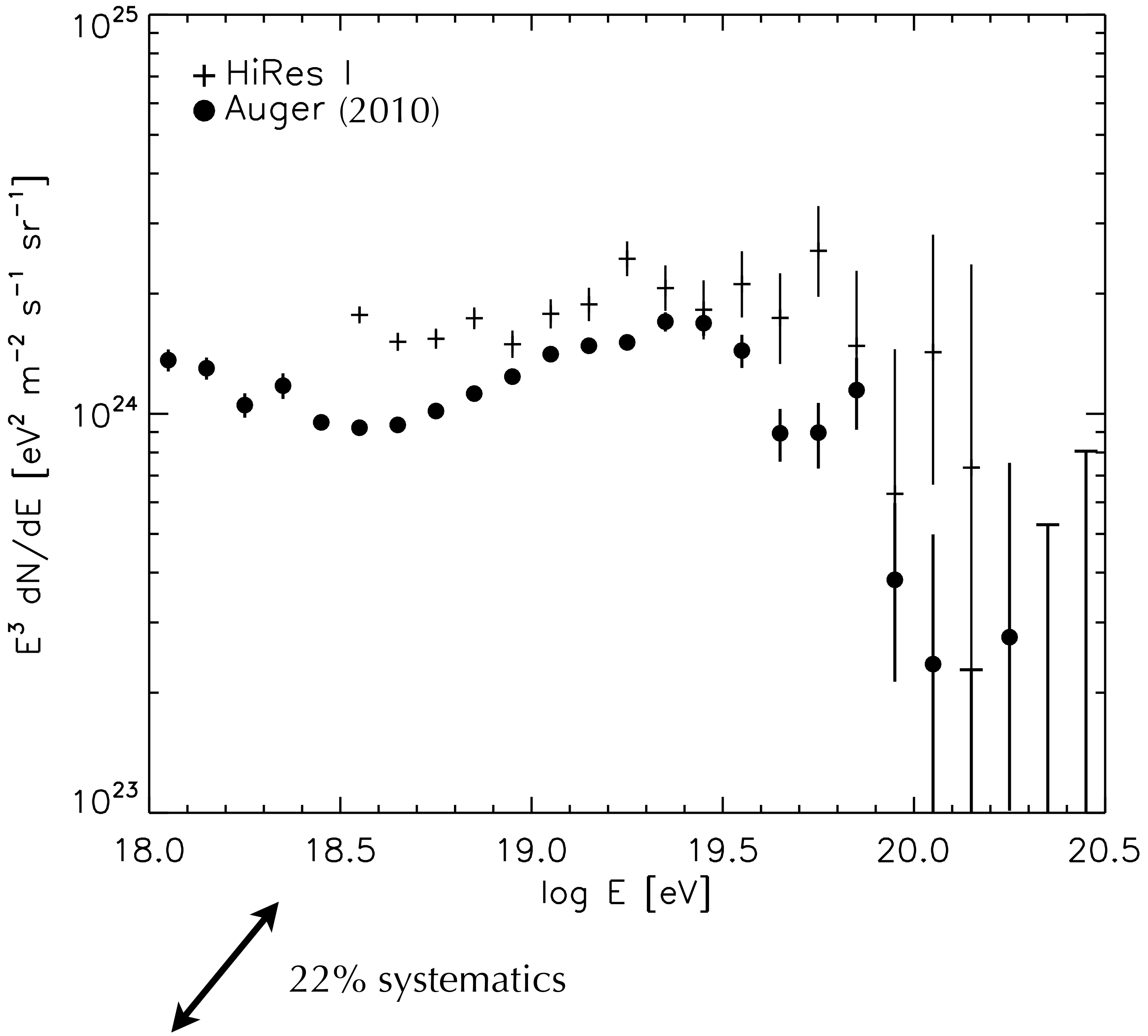


chemical composition



other messengers:
secondary gamma-rays,
neutrinos

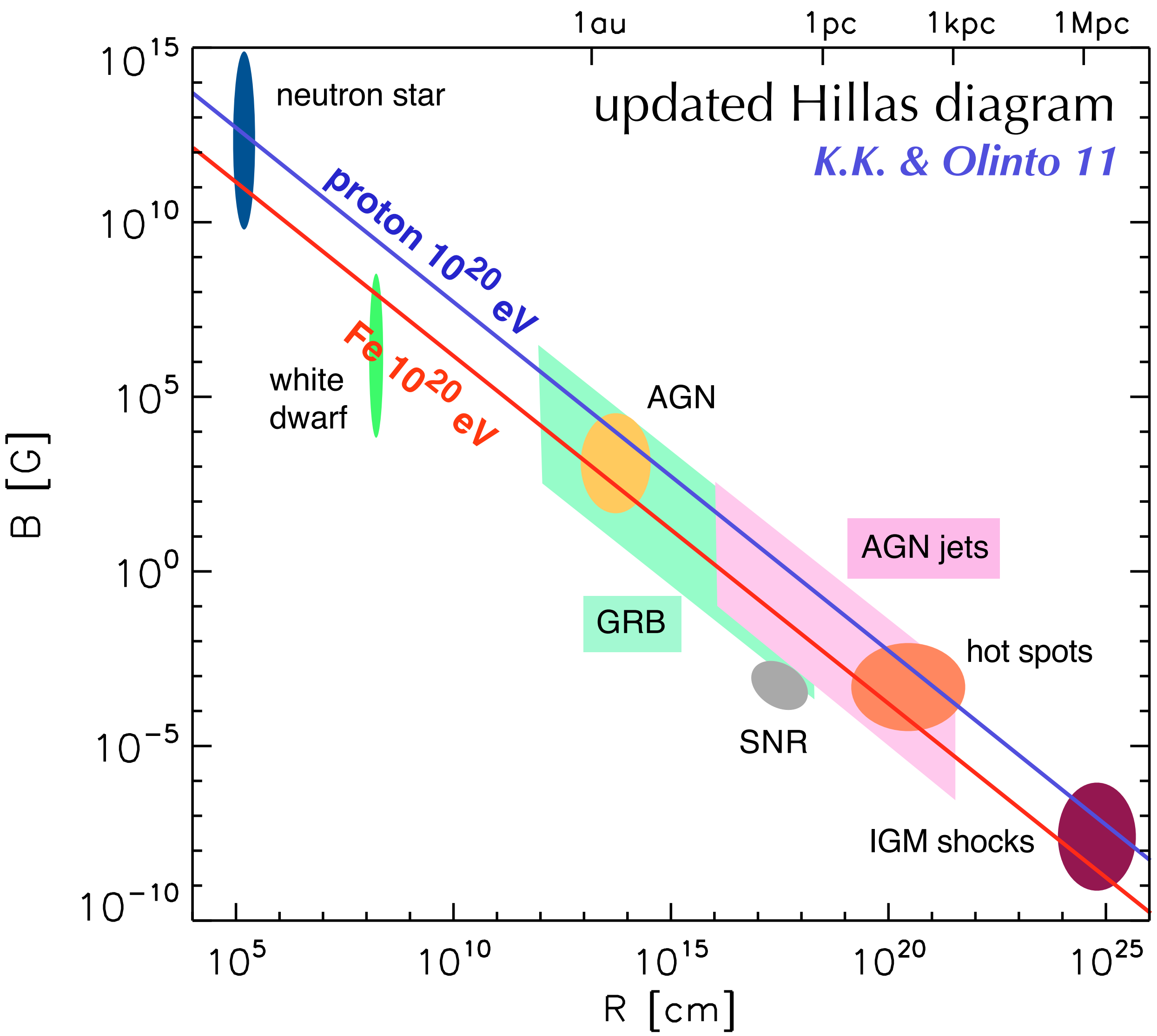
Crucial information from the energy spectrum



UHECR energy budget [@E=10^{19} eV]:
$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5x10^{44} erg Mpc^{-3} yr^{-1}
Katz et al. 09

acceleration to E>10^{20} eV
necessary magnetic luminosity
($L_B \equiv \varepsilon_B L_{outflow}$):
$L_B > 10^{45.5}$ erg/s Γ^2 β^{-1}
Lemoine & Waxman 09

$E_{UHECR} > 10^{20}$ eV: first selection of sources

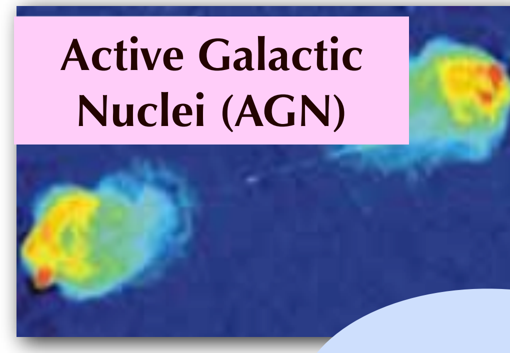


confinement of particle in source:
particle Larmor radius < size of source

$$r_L \leq L$$

$$r_L = 1.08\ \mathrm{Mpc}\ Z^{-1} \left(\frac{E}{10^{18}\ \mathrm{eV}}\right) \left(\frac{B}{1\ \mathrm{nG}}\right)^{-1}$$

! caution when applied to relativistic outflows



black holes/jets/hot spots
acceleration limited
by radiation losses
e.g. Norman et al. 1995, Rachen & Biermann 1995, Henri et al. 1999, ...moine & Waxman 2009

steady sources

...etion shocks
... ~ 1-10 Mpc, $B_{downstr}$ ~ 1 μG
--> E ~ 10^{20} eV ?
but maybe $B_{upstream}$ << 1 μG
e.g. Kang et al. 1997, Miniati et al., 2000, Murase et al. 2008

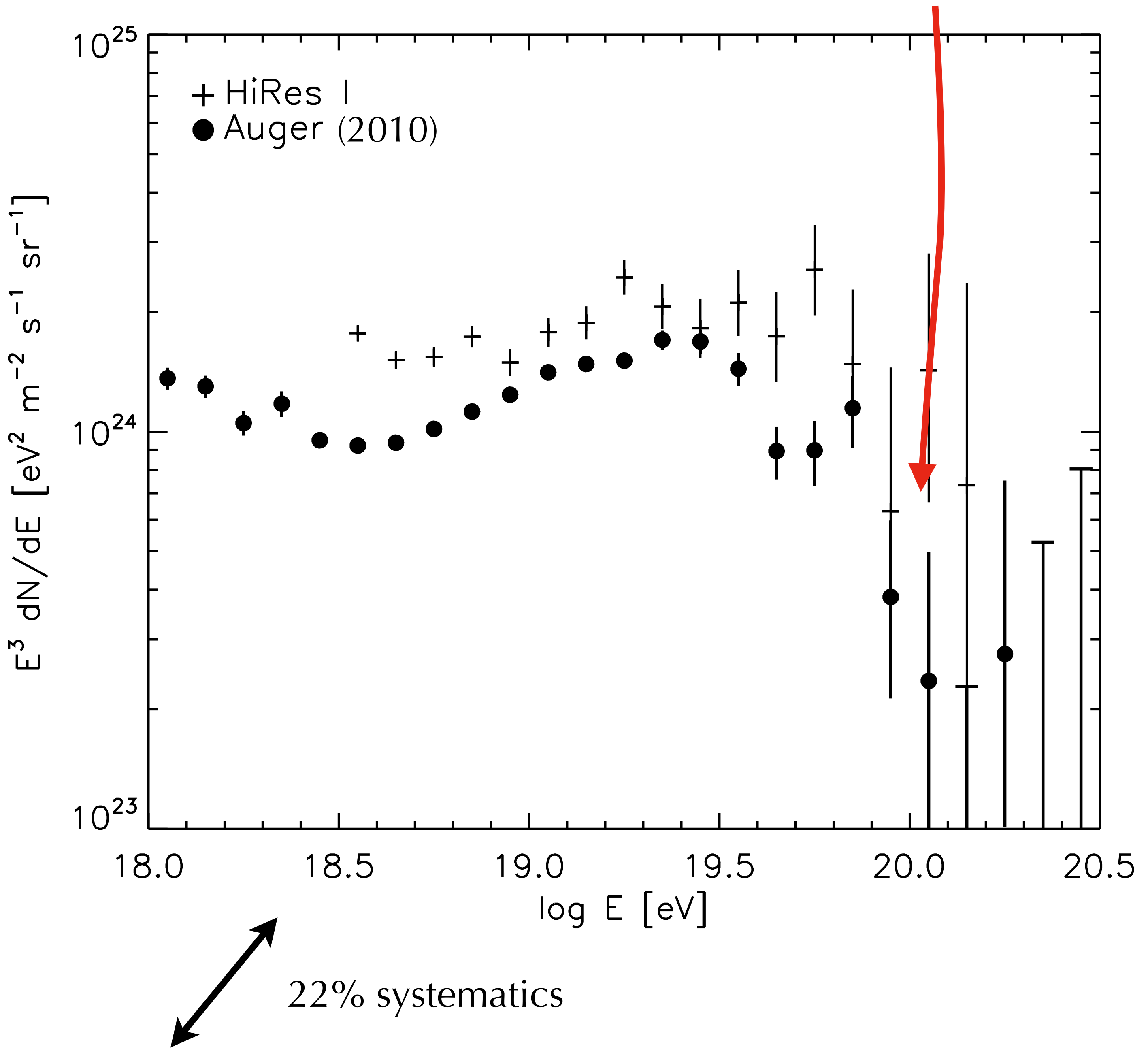
accelation ok,
but tight energy budget
because rare source
e.g. Waxman 1995, ...tri 1995, Murase 2008

transient sources

very promising for
fast-spinning magnetized
ones!
Fang, K.K., Olinto, Fryer, in prep.

maximum acceleration energy?

or GZK cut-off?



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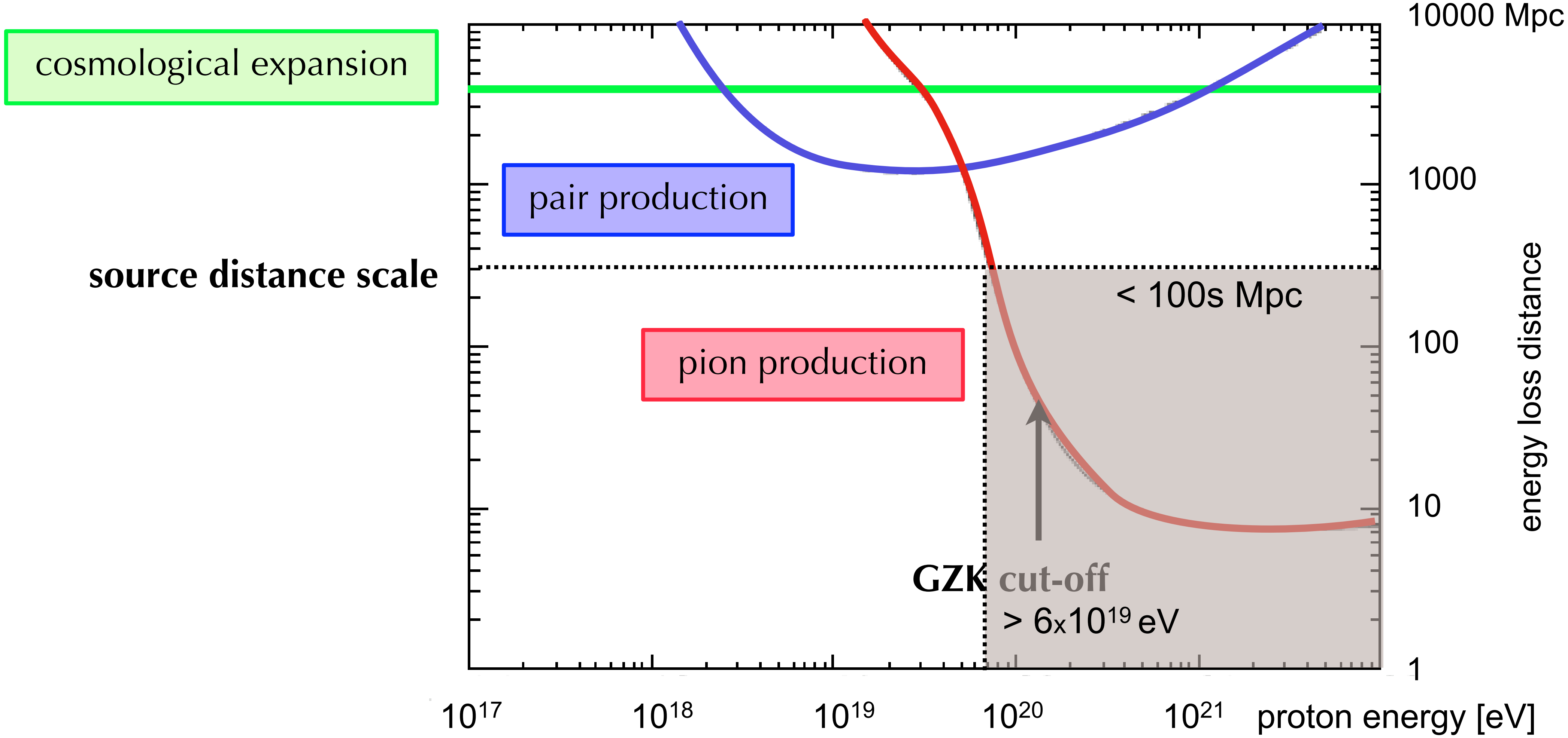
Lemoine & Waxman 09

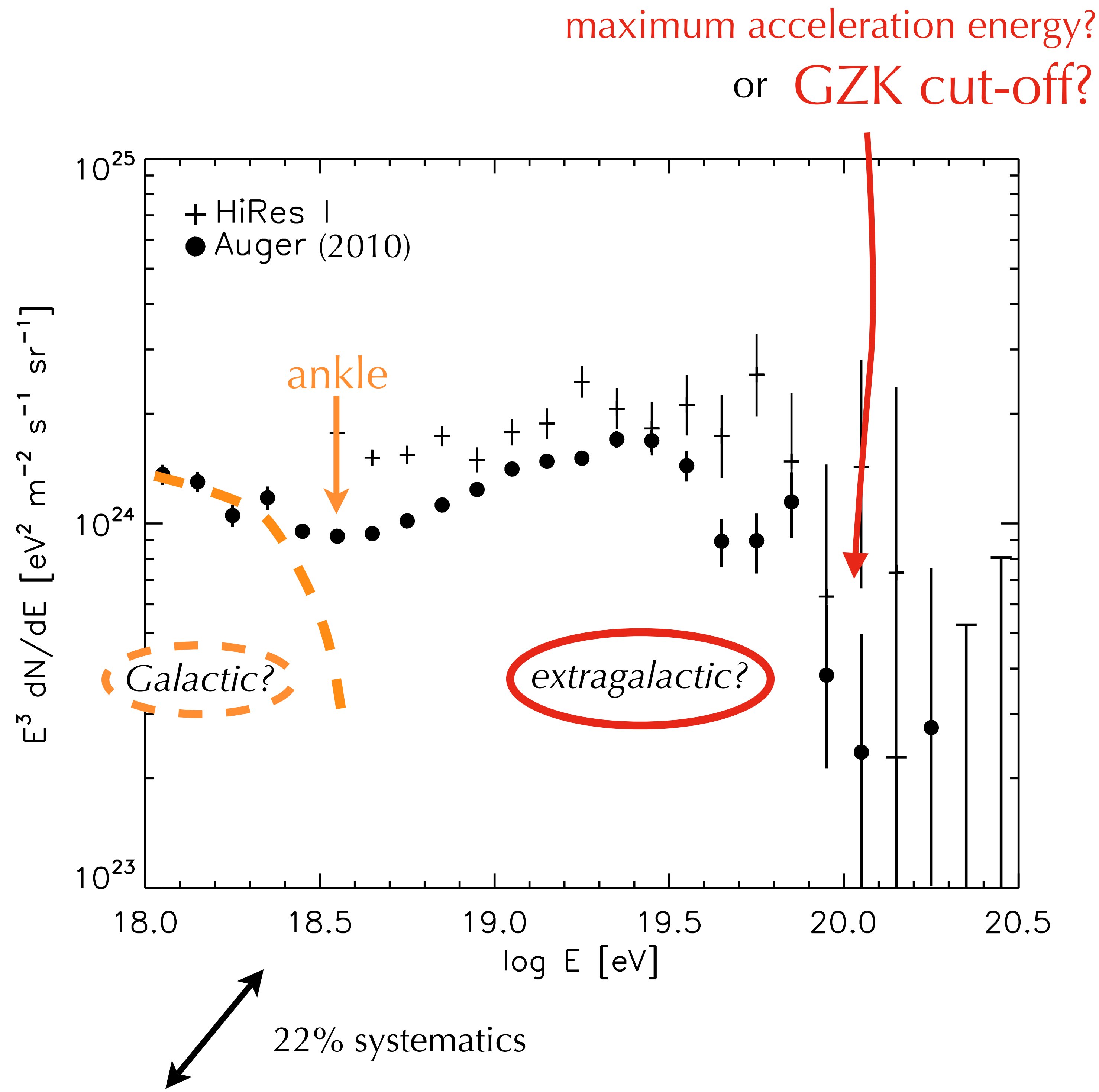
Energy losses for UHECRs

for proton cosmic rays: backgrounds: CMB IR/optical/UV photons

pion photoproduction	$p + \gamma \longrightarrow N + n\pi$	$E_p \gtrsim \frac{m_\pi(m_\pi + 2m_p)\,c^4}{2\epsilon} \sim$ 6 x10^{19} eV
pair photoproduction	$p + \gamma \longrightarrow p + e^+ + e^-$	$E_p \gtrsim \frac{m_e m_p}{\epsilon} \sim 10^{19}$ eV



Crucial information from the energy spectrum



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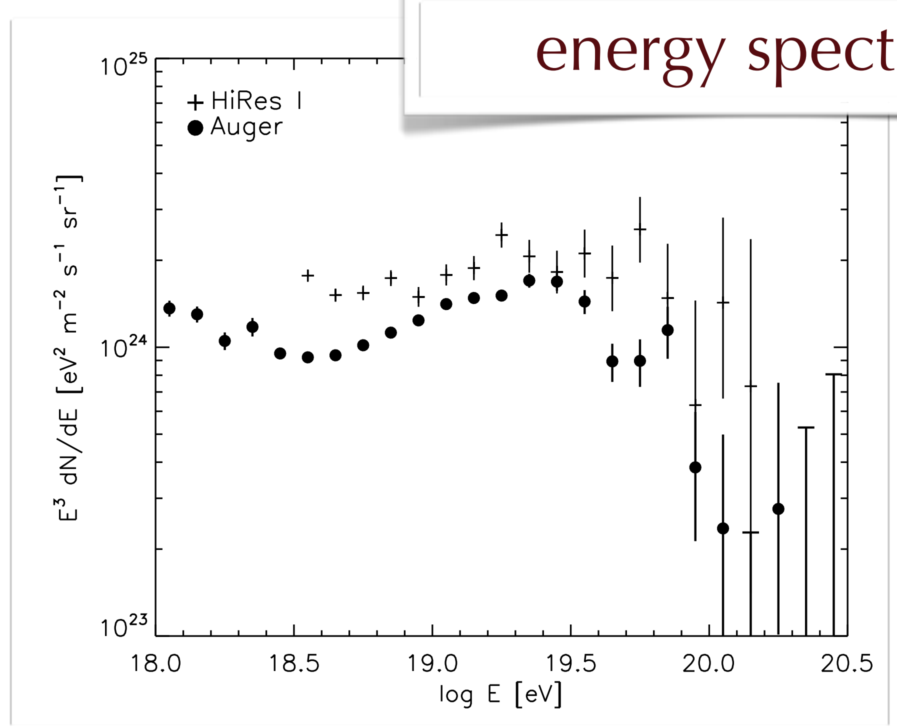
Lemoine & Waxman 09

for particles with E > $E_{\rm GZK}$ (~6×10^{19}eV)
sources within ~ few 100 Mpc

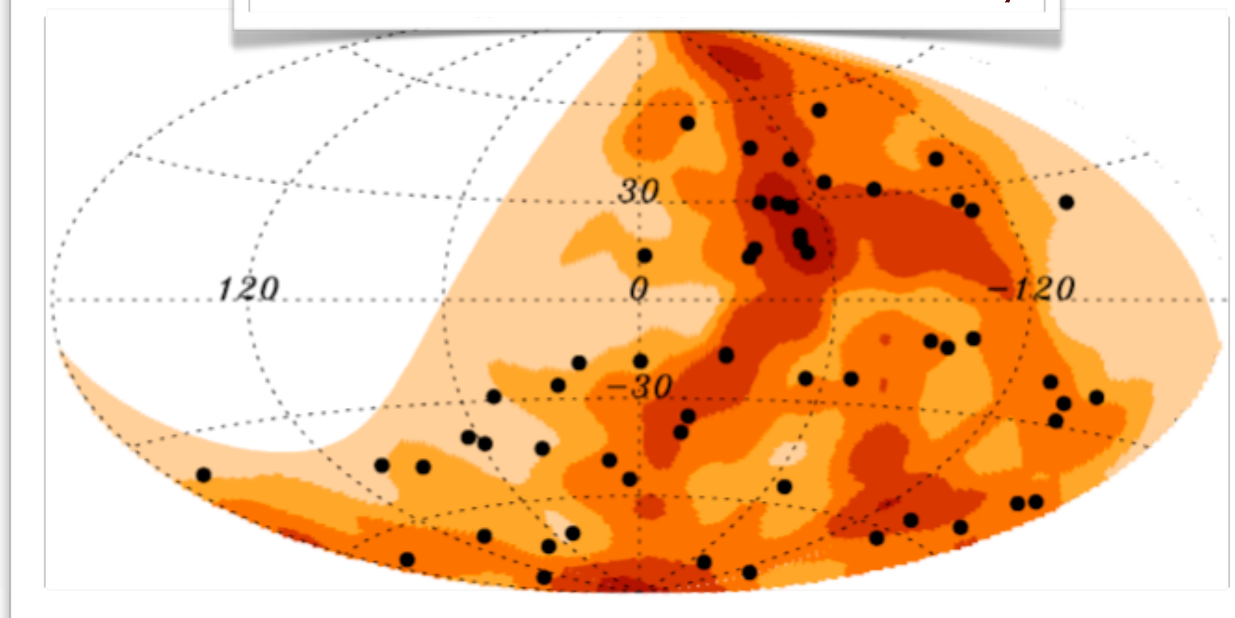
ankle @ E~$10^{18.5}$ eV:
Galactic/extragalactic transition?

What observational information do we have?

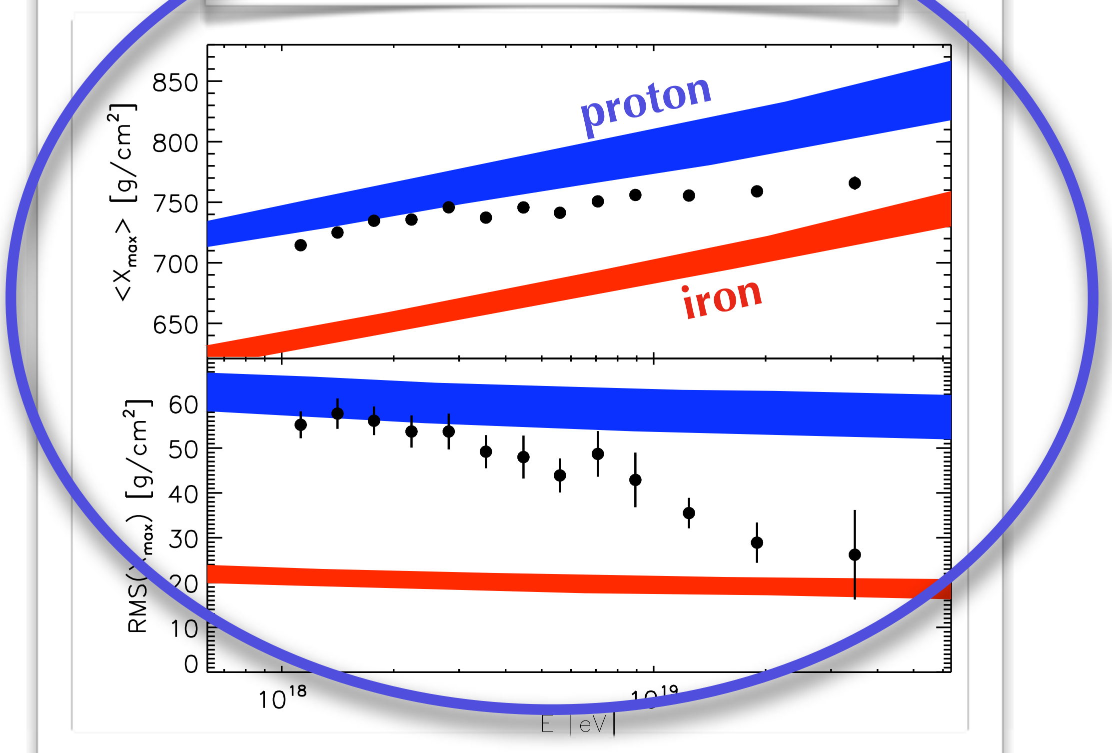
energy spectrum



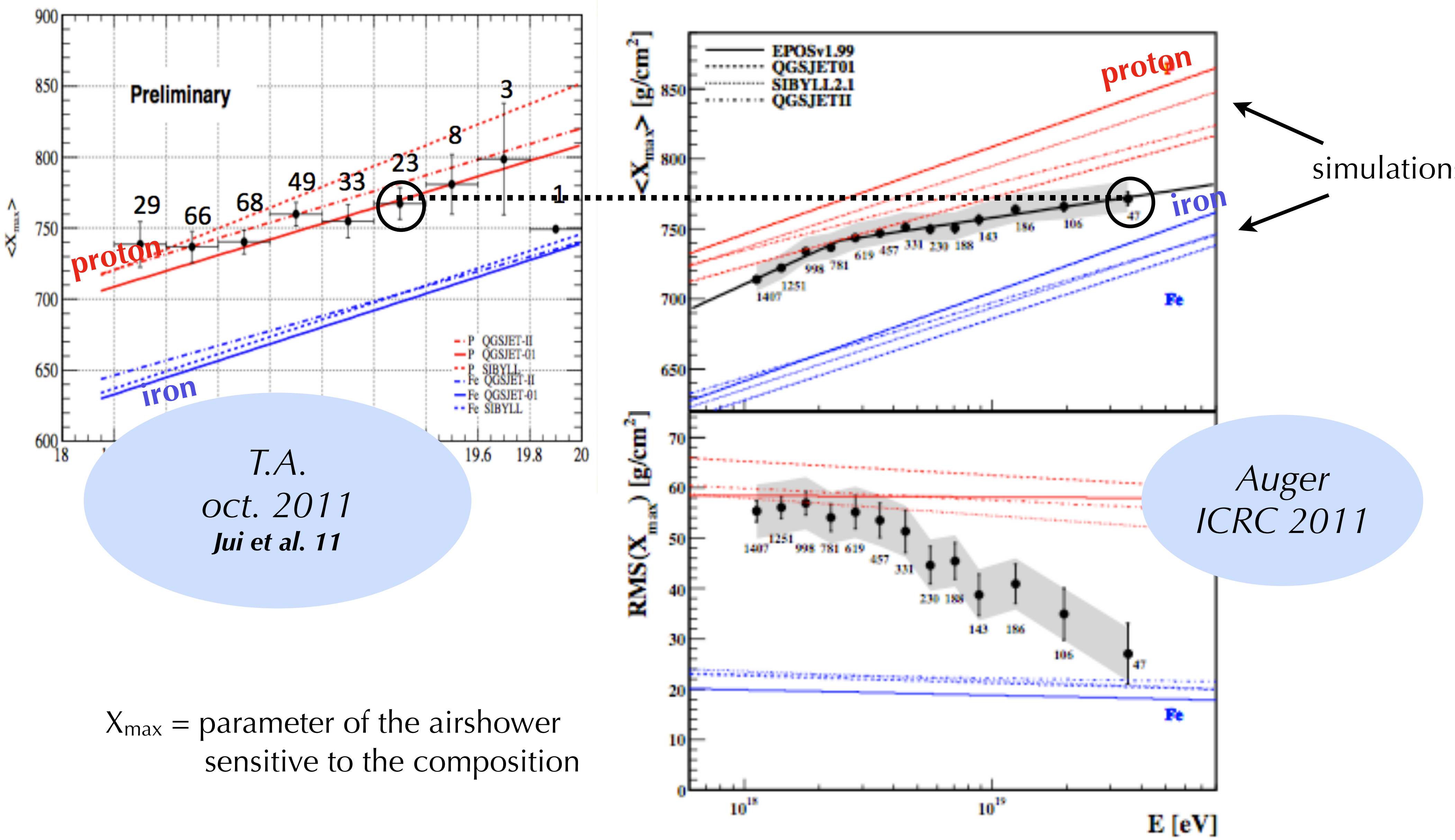
arrival directions in the sky



chemical composition



other messengers:
secondary gamma-rays,
neutrinos

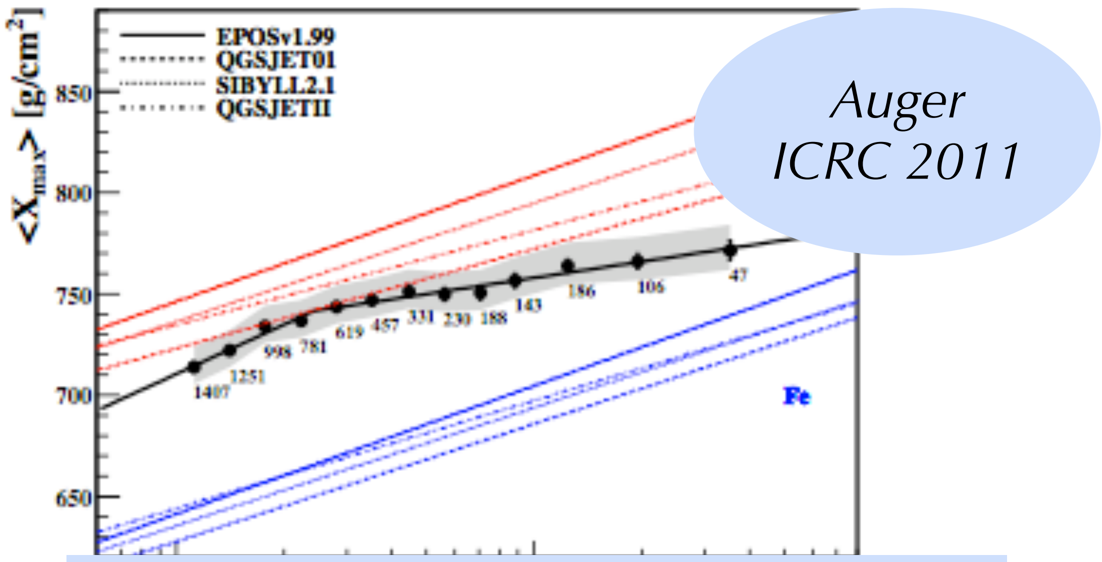


X_{max} = parameter of the airshower sensitive to the composition

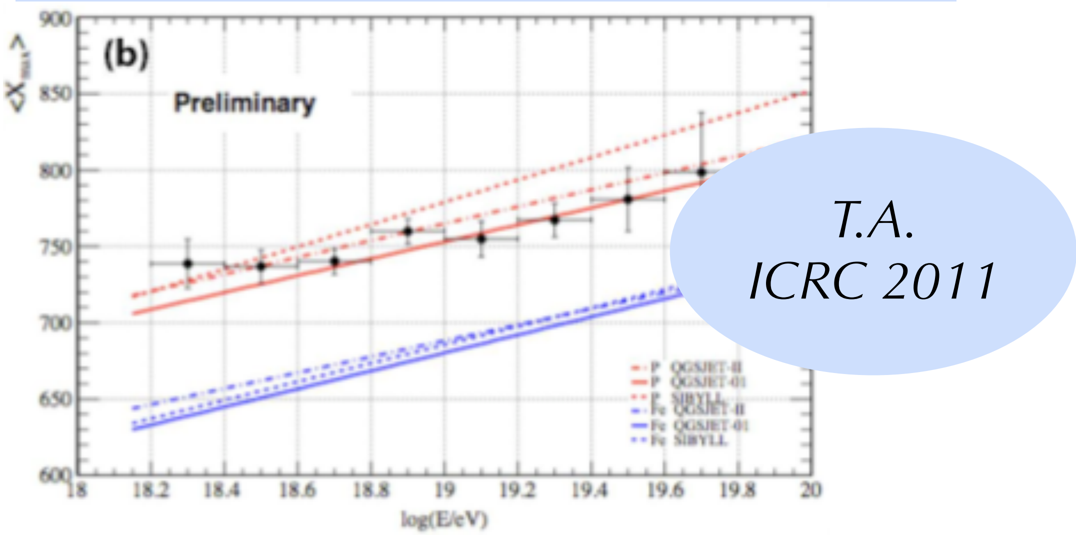
HiRes, TA --> protons?
all results compatible within systematics

??? what composition is that ???

Puzzling composition measurements



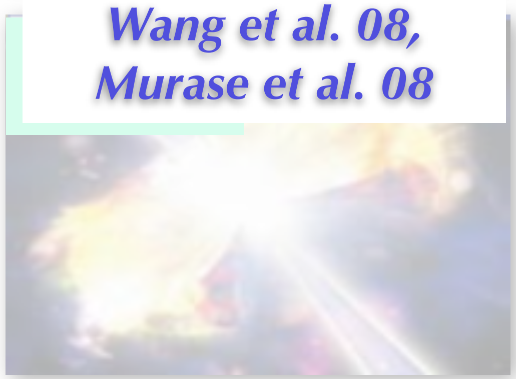
??? what composition is that ???



at the sources:
heavy nuclei if **metal-rich** or **nucleosynthesis**
escape difficult due to **photo-disintegration** in source?

heavy nuclei?

e.g., Lemoine 02, Pruet et al. 02, Wang et al. 08, Murase et al. 08

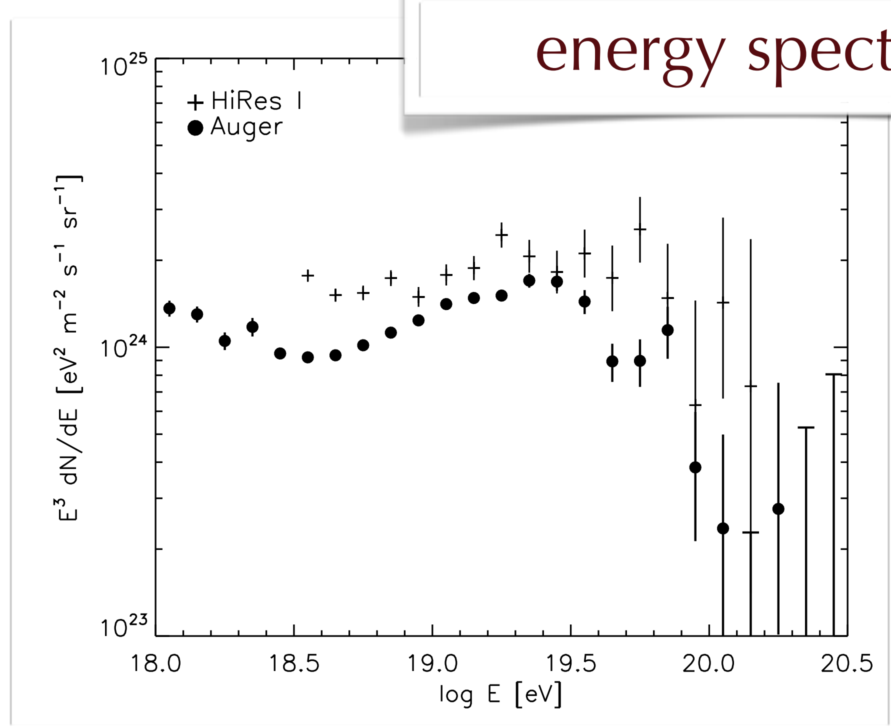


e.g., Ruderman & Sutherland 75, Arons & Scharlemann 79, Blasi et al. 00, Fang et al. in prep.

metal-rich surface, iron could escape

What observational information do we have?

energy spectrum



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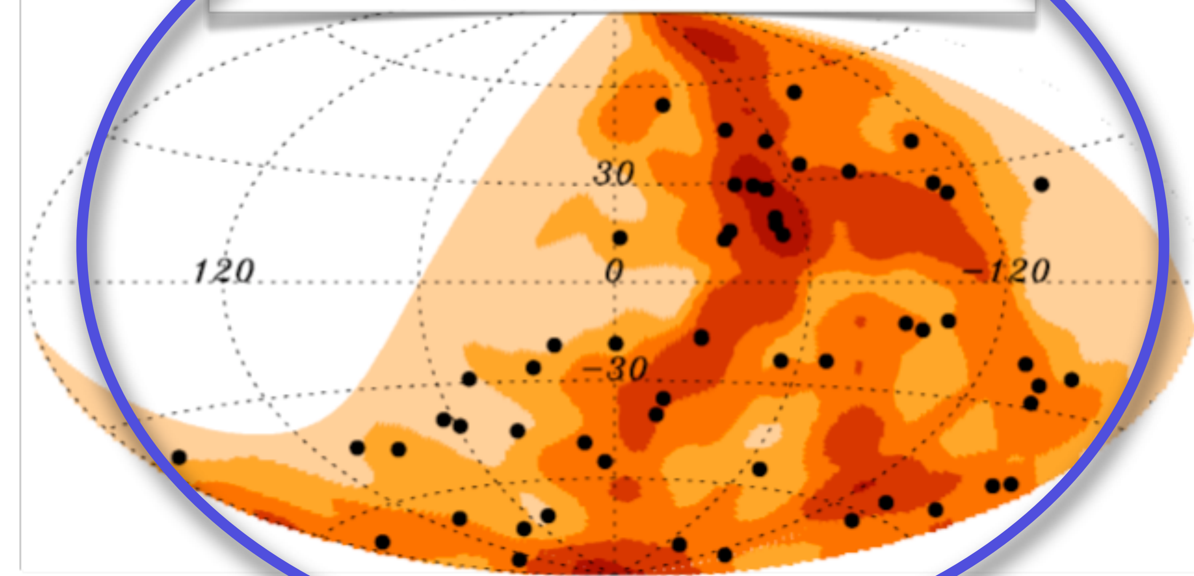

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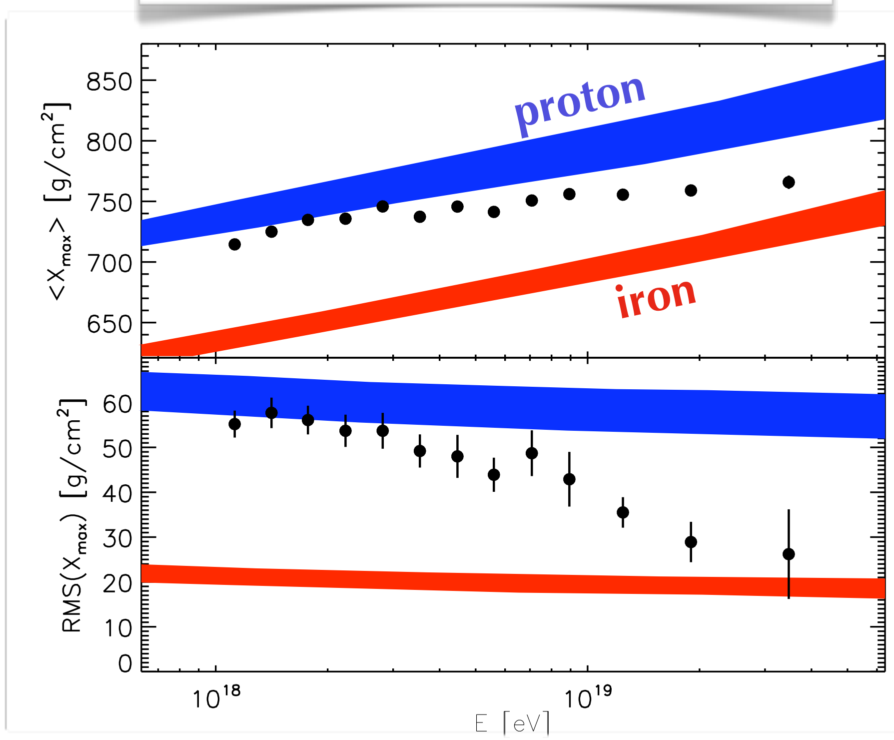

other messengers:
secondary gamma-rays,
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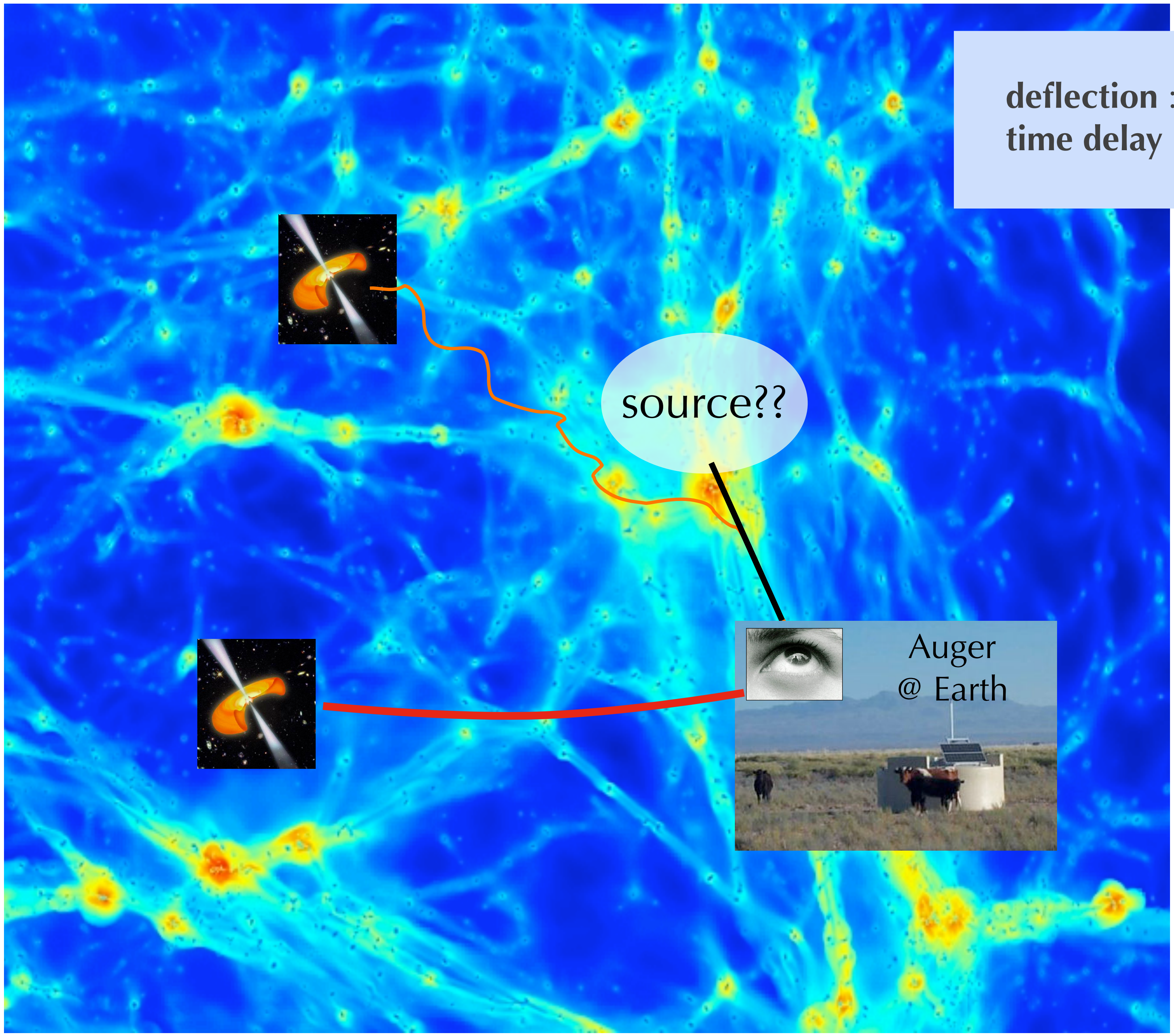
Arrival directions in the sky & magnetic fields



deflection : spatial decorrelation
time delay : temporal decorrelation if transient source

Extragalactic magnetic fields?

poorly known (no observation)
upper limits: B $l_{coh}^{1/2}$ < 1-10 nG Mpc$^{1/2}$
simulations --> complex and contradictory

Beck 08, Vallée 04, Dolag et al. 05, Sigl et al. 05, Ryu et al. 98, Donnert et al. 09...

Propagation of UHECR in extragalactic magnetic fields?

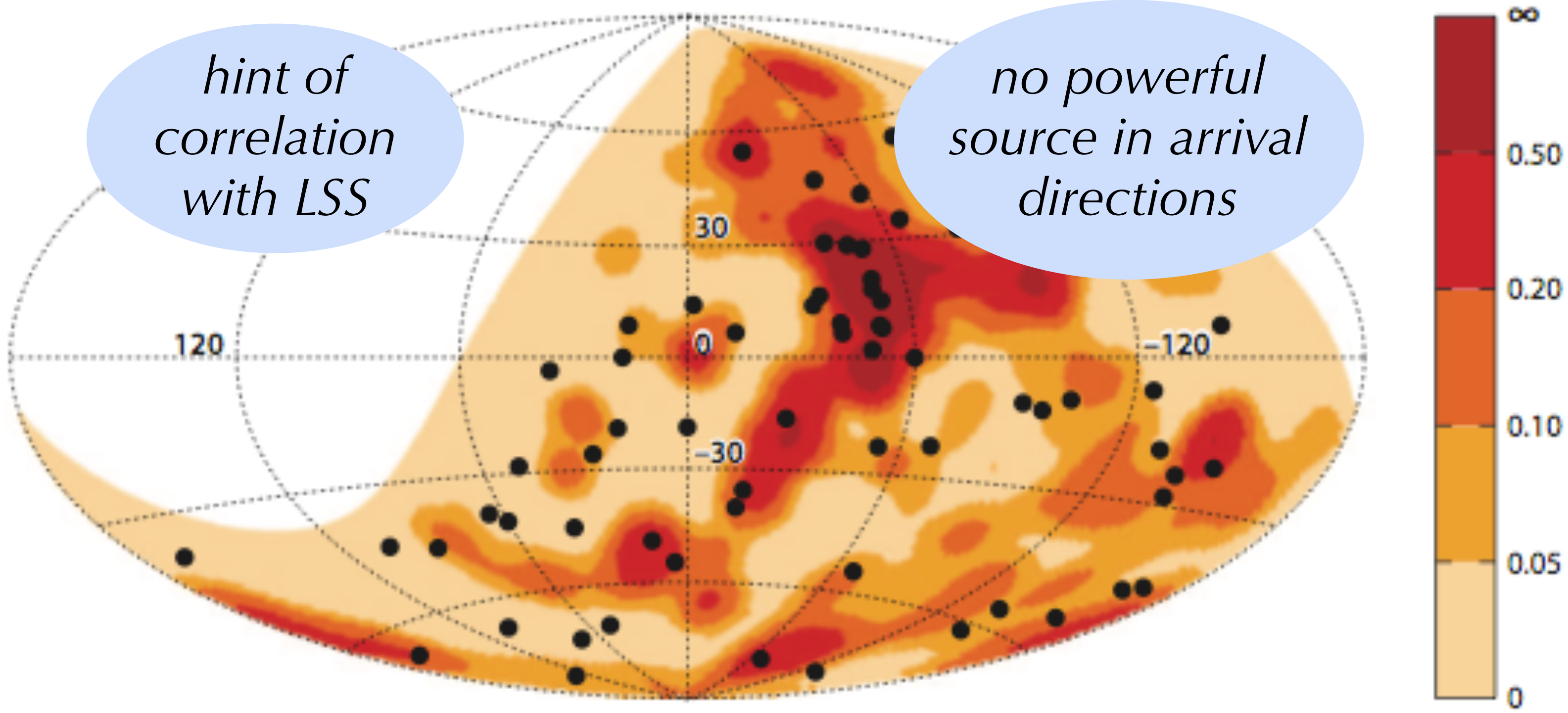
complicated because B not known

e.g., Dolag et al. 05, Sigl et al. 05, Ryu et al. 98, Takami & Sato 08, KK & Lemoine 08

+ Galactic magnetic fields...

Arrival directions in the sky seen by Auger

density map of Swift-BAT



steady sources? **OR** **transient source?**

- particularly strong extragalactic magnetic field
- UHECR = heavy nuclei

source already extinguished when UHECR arrives
correlation with LSS with no visible counterpart

no correlation with
secondary neutrinos, photons, grav. waves

>165 events (>4 years with Auger South)
to reach a 5σ significance

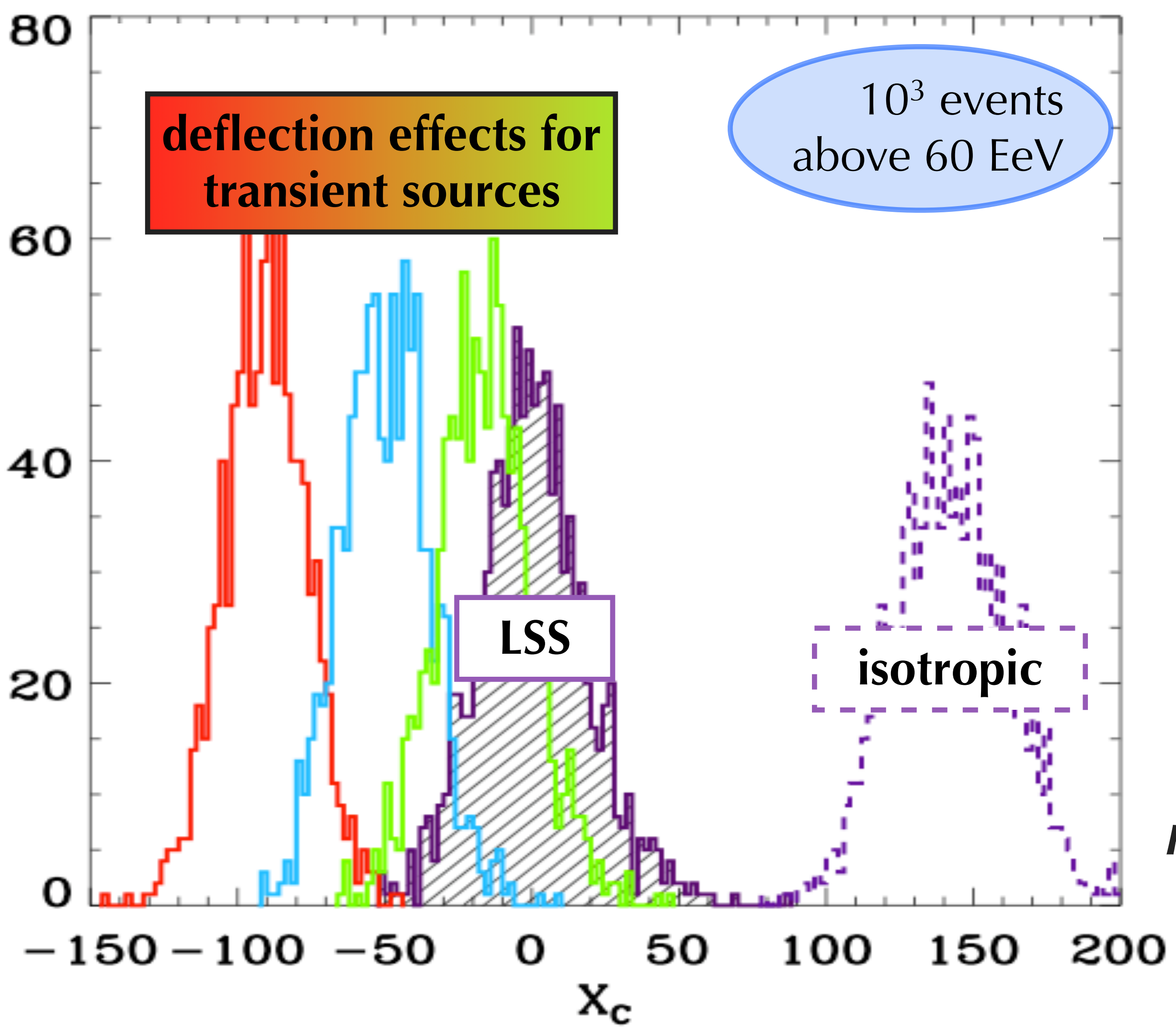
Will better statistics help?

Separate source populations with anisotropy

YES

time delay effects (deflections in magnetic fields)
-> distribution of UHECRs for **transient sources** different from LSS

separation possible for

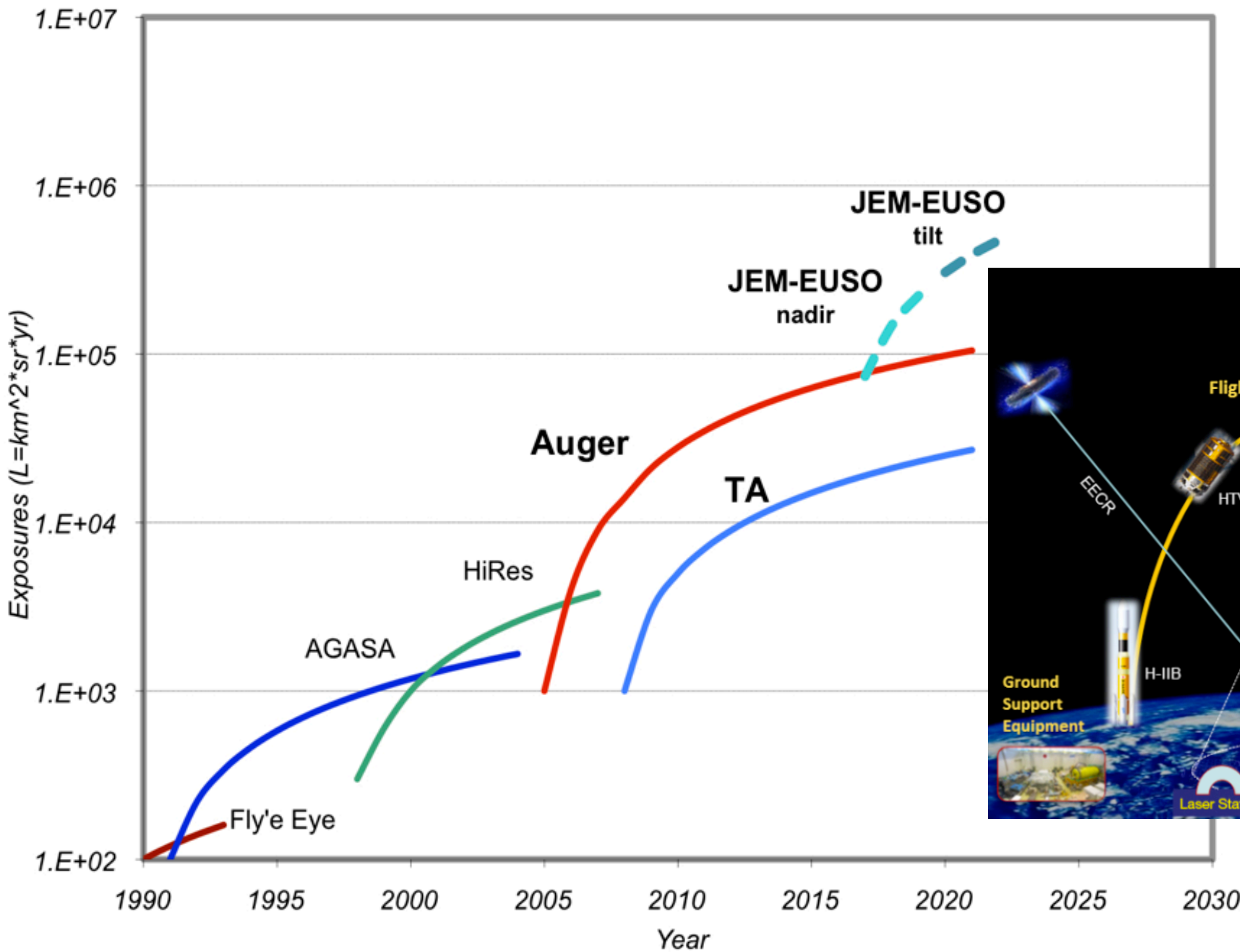


Kalli, Lemoine, K.K., 2011

measurement of correlation btw observed and predicted event distributions

$$X_C = \sum_{i=1}^{N_{tot}} \frac{(N_i^T - \langle N_{i,\mathrm{LSS}}\rangle)(\langle N_{i,\mathrm{iso}}\rangle - \langle N_{i,\mathrm{LSS}}\rangle)}{\langle N_{i,\mathrm{LSS}}\rangle}$$

A clear necessity: increasing the statistics...

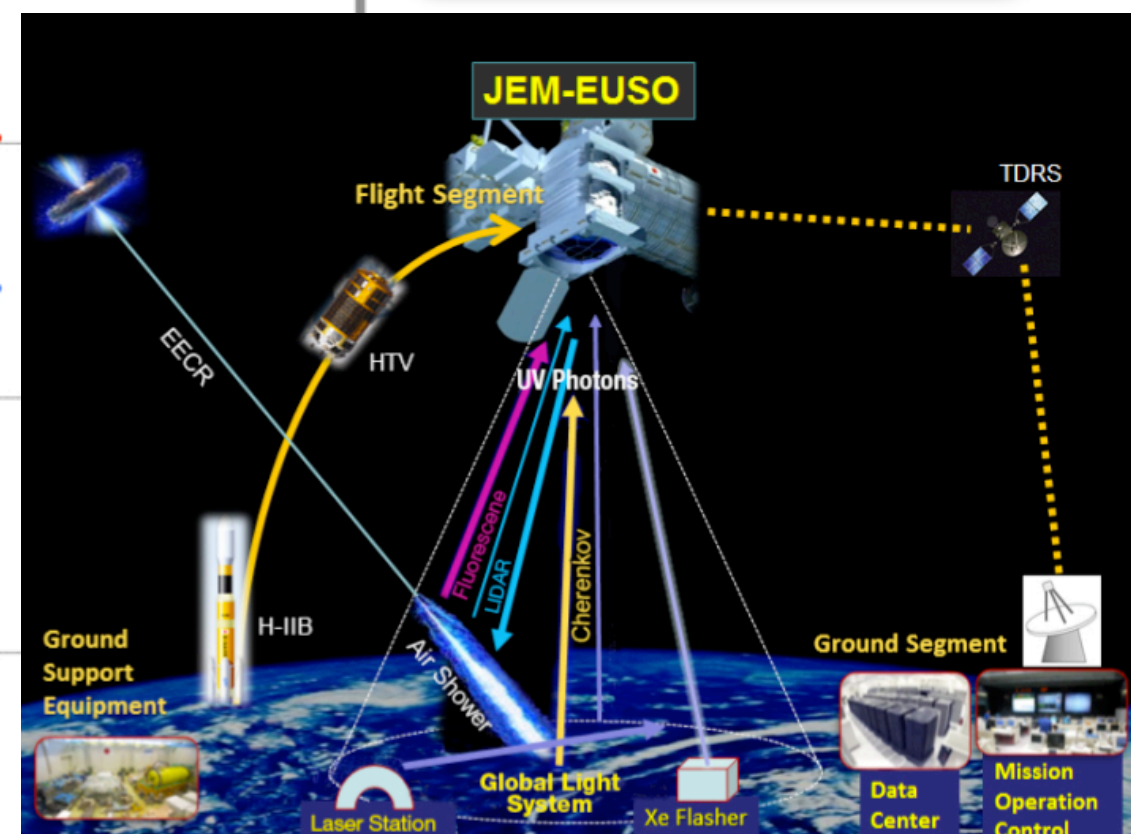


JEM-EUSO

$E_{th} > 10^{20}$ eV

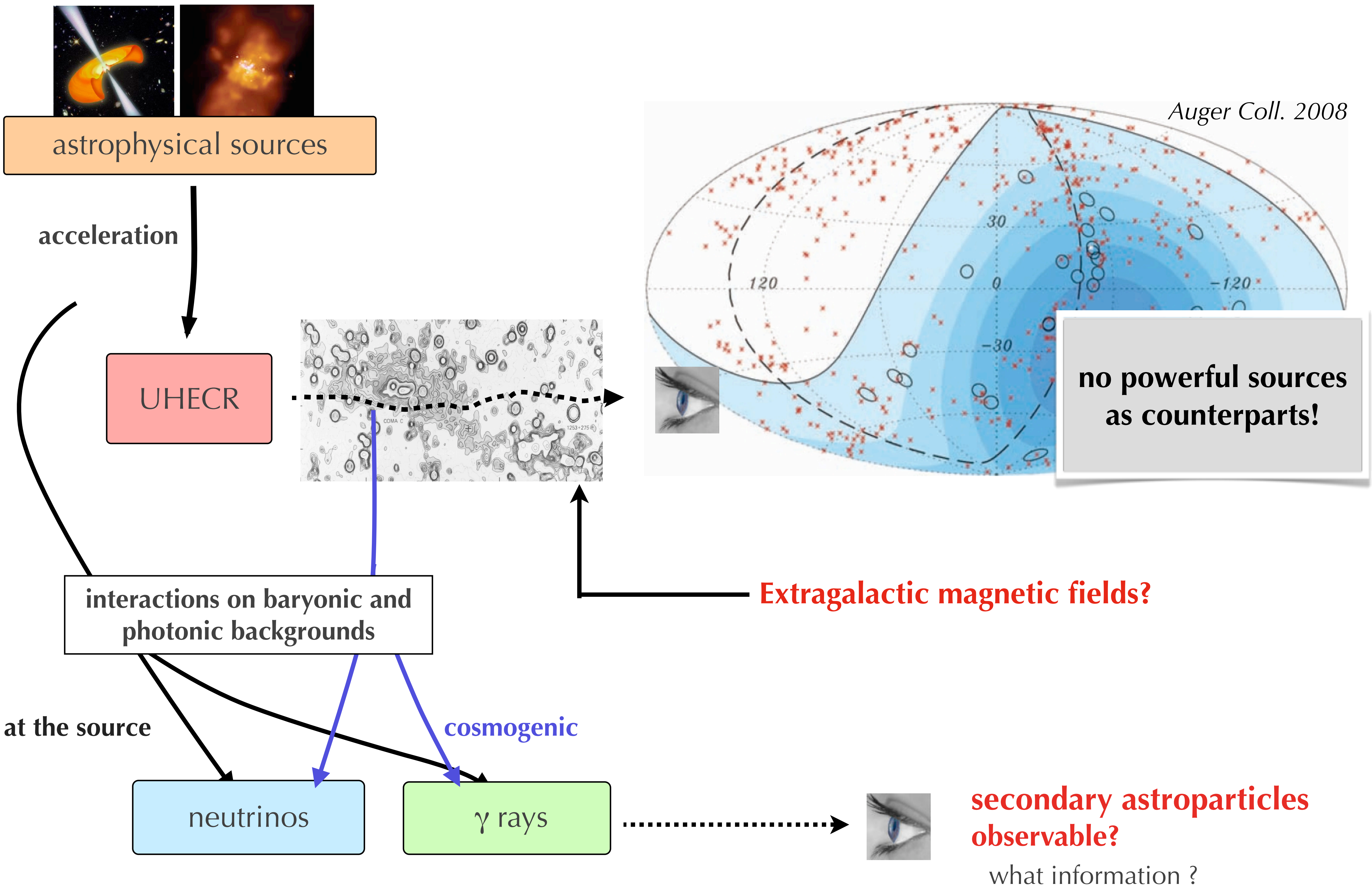
duty cycle 20%

Auger S x (~30)



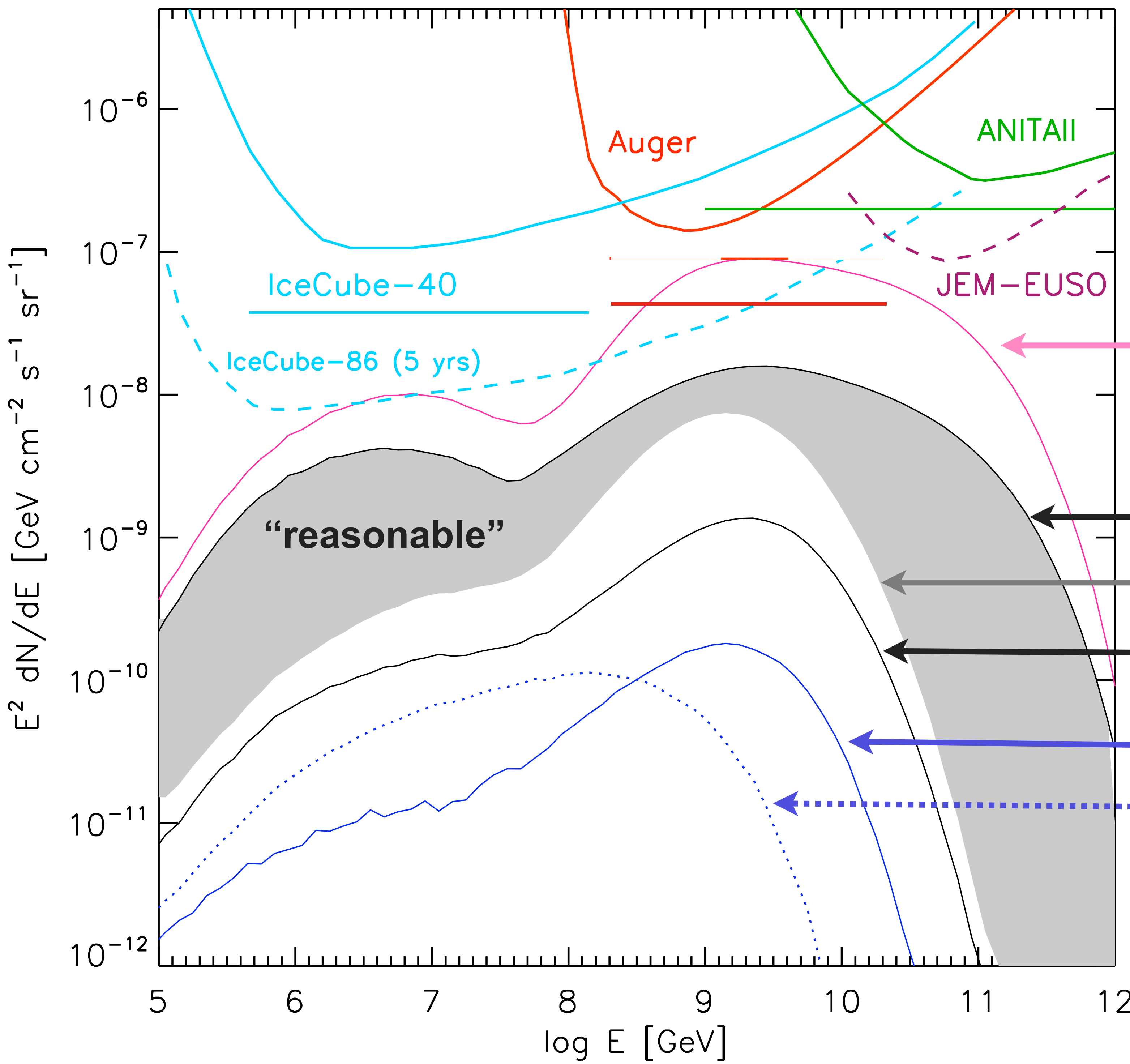
Adams et al. 2012, arXiv:1203.3451

... and look at other messengers



What cosmogenic neutrinos could tell us

K.K., Allard & Olinto, 2010
see also Decerprit & Allard 2011



cosmogenic neutrino fluxes
and instrument sensivities

FRII galaxies and other sources with strong emissivity evolution
excluded by Fermi (diffuse gamma ray flux)
Ahlers et al., 2010; Berezinsky et al., 2010
by Auger and soon by IceCube

proton dominated dip model

proton dominated ankle model

proton dom., no source evolution

pure iron, no source evolution

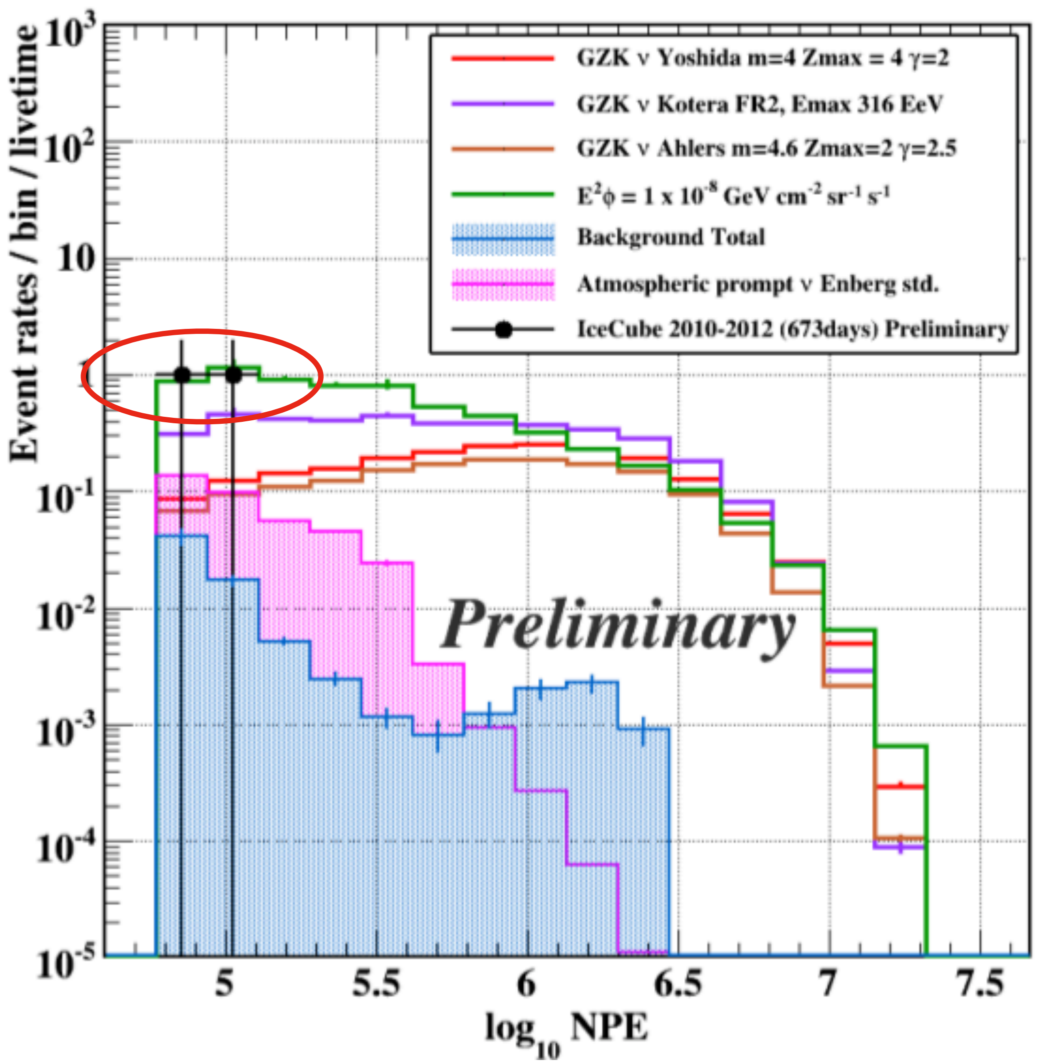
iron rich, no source evolution

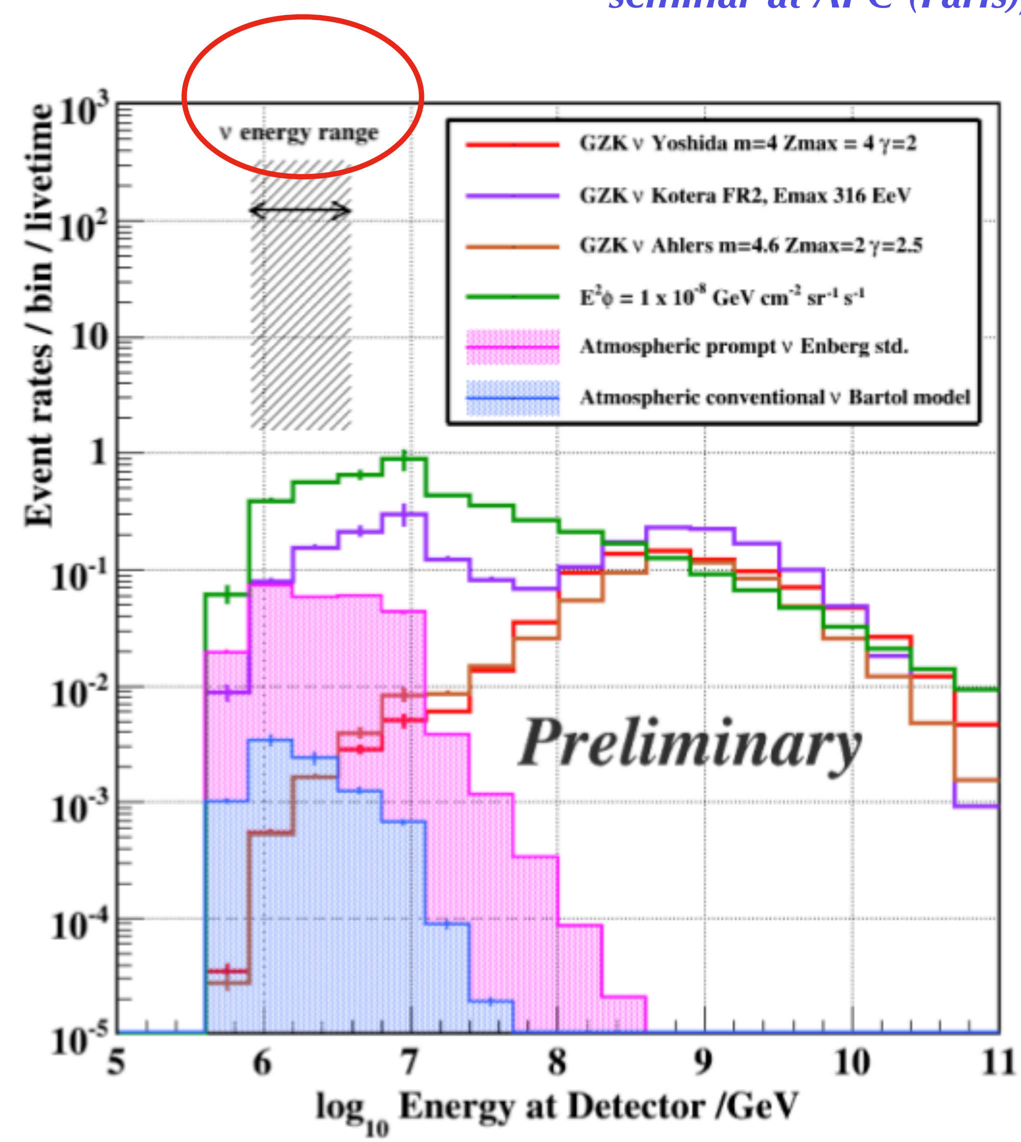
1) FRII galaxies excluded
2) reasonable models within reach?
3) there is a bottom

What if the IceCube PeV neutrino detection were true?

2.46-σ measurement of 2 events at PeV energies

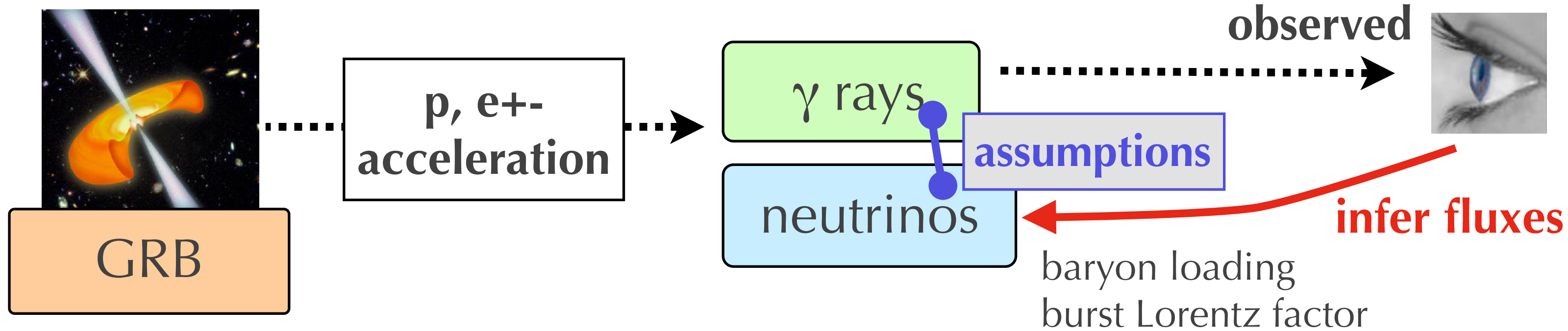
S. Yoshida for the IceCube Coll., seminar at APC (Paris), April 2012





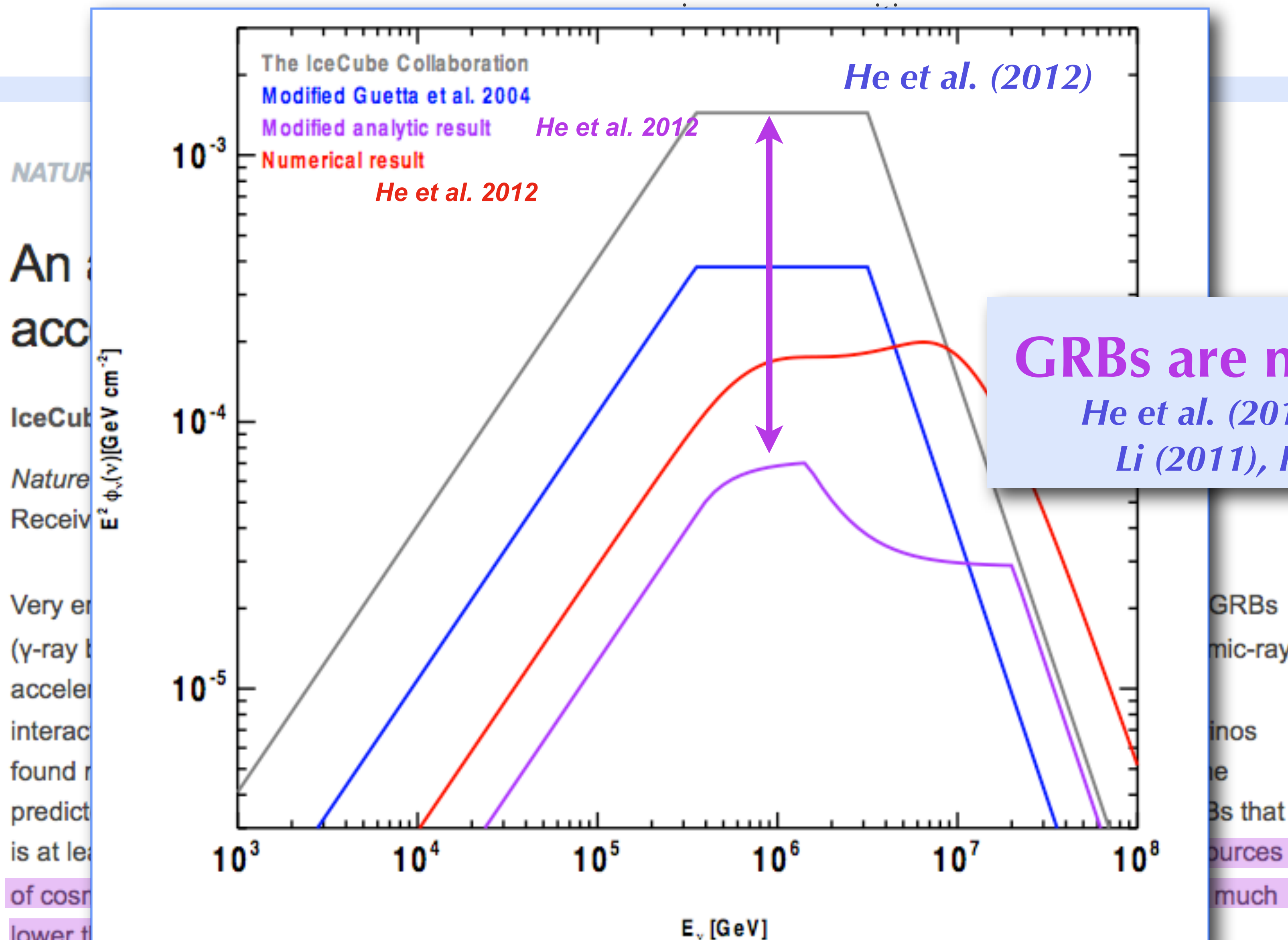
- does not look atmospheric
- FRII source evolution already ruled out
- **probably not cosmogenic neutrinos**
- neutrinos produced at sources --> **evidence of UHECRs ~ 10^{17} eV**
- either **Galactic** source --> check arrival direction, correlate with Galactic source catalogues
- or **extragalactic** source if nothing in the Galaxy. If source is not transient, possible correlation with extragalactic source.

Neutrino fluxes expected at the source



baryon loading
burst Lorentz factor
Emin, Emax of cosmic rays
acceleration region (internal/external/reverse shock?)

e.g., Waxman & Bahcall limit (1997)

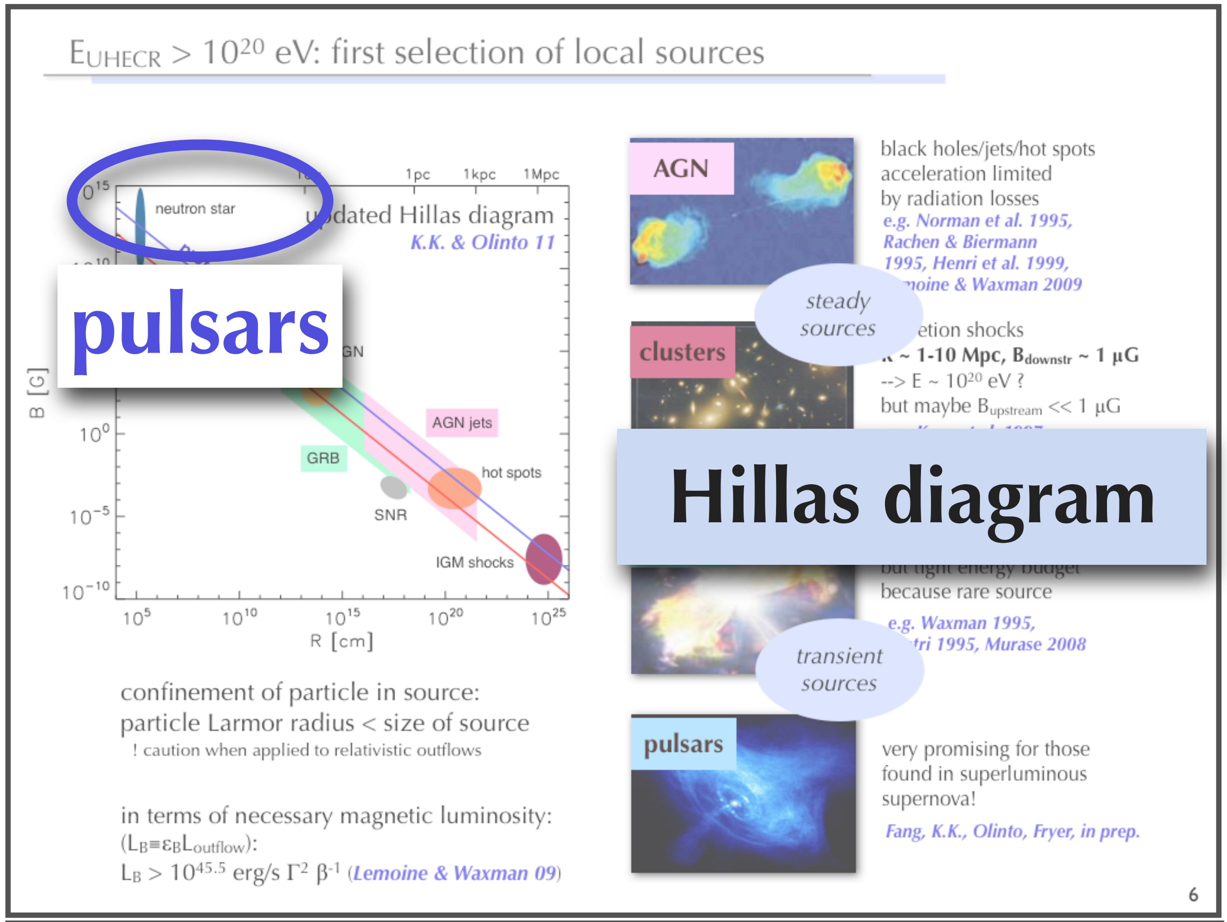


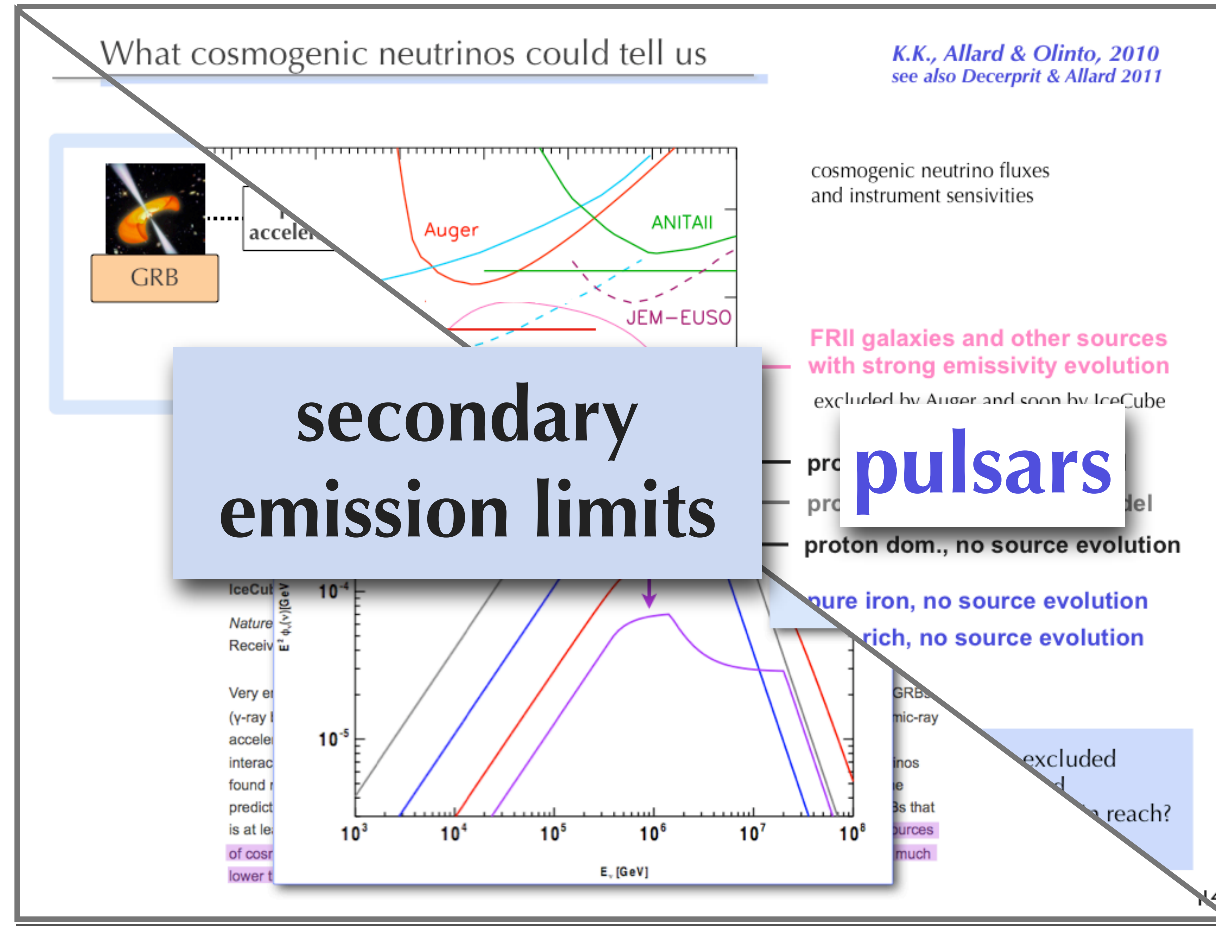
GRBs are not ruled out yet...

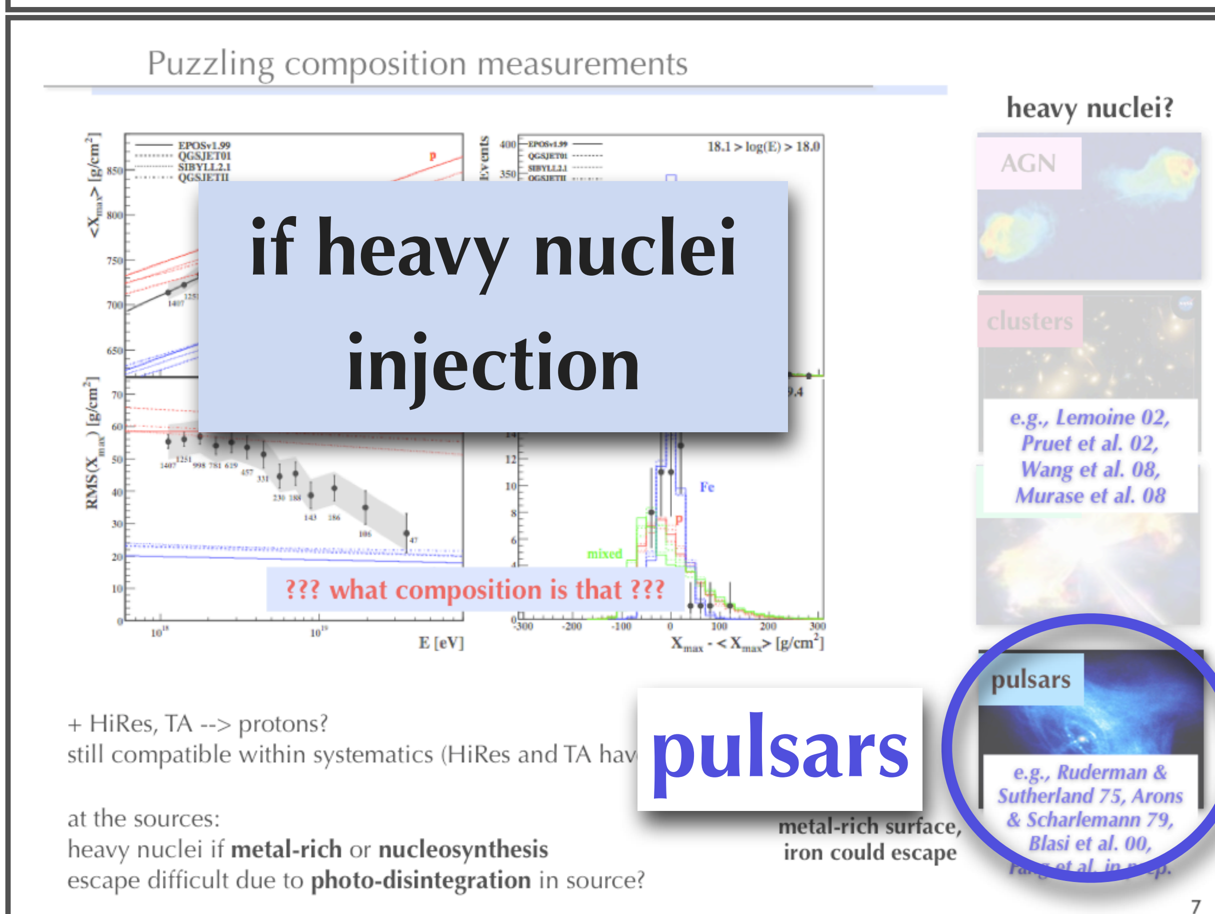
He et al. (2012) arXiv:1204.0857

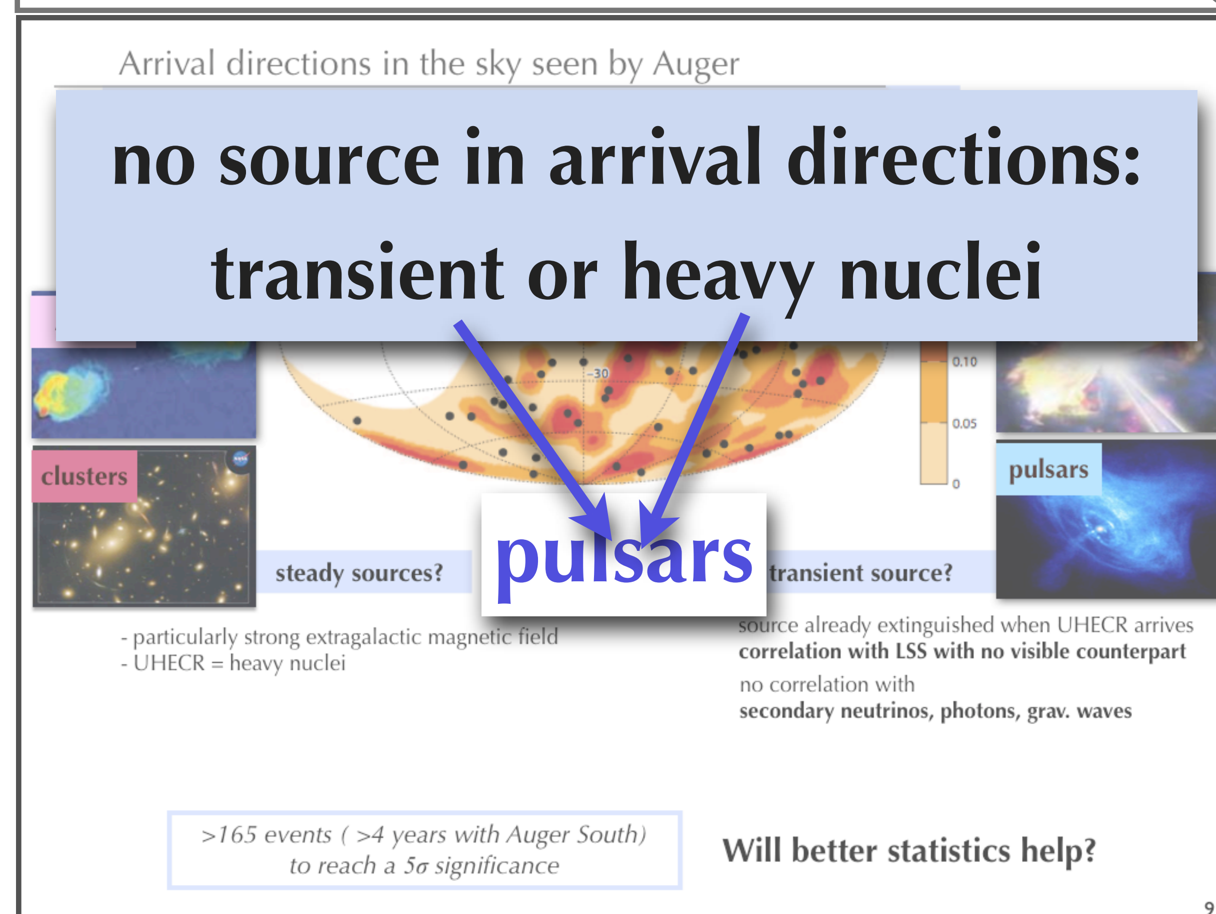
Li (2011), Hümmer (2011)

Meanwhile, case/case study of sources…









Acceleration of UHECR in newly-born ms pulsars

Blasi et al. 00,
Arons 03,
Fang, KK, Olinto 2012

unipolar induction in the pulsar wind

strong magnetic field $\mathbf{B}$
fast rotation velocity $\mathbf{\Omega}$

$$\mathbf{E} = -\mathbf{\Omega} \times \mathbf{B}$$

particles accelerated to energy:

$$E(\Omega) \sim 8.6 \times 10^{20}\, Z_{26}\, \eta_1\, \Omega_4^2\, \mu_{31}\ \mathrm{eV}$$

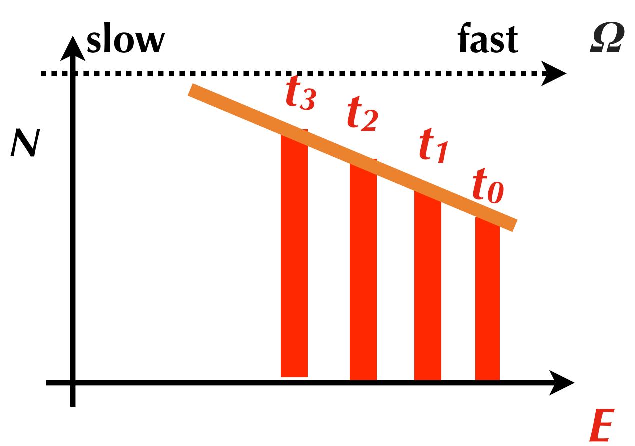
10%: fraction of voltage experienced by particles

magnetic moment 10^{31} cgs ($B \sim 10^{13}$ G)

rotation velocity 10^4 s^{-1}

pulsar spins down

energy spectrum for one pulsar:

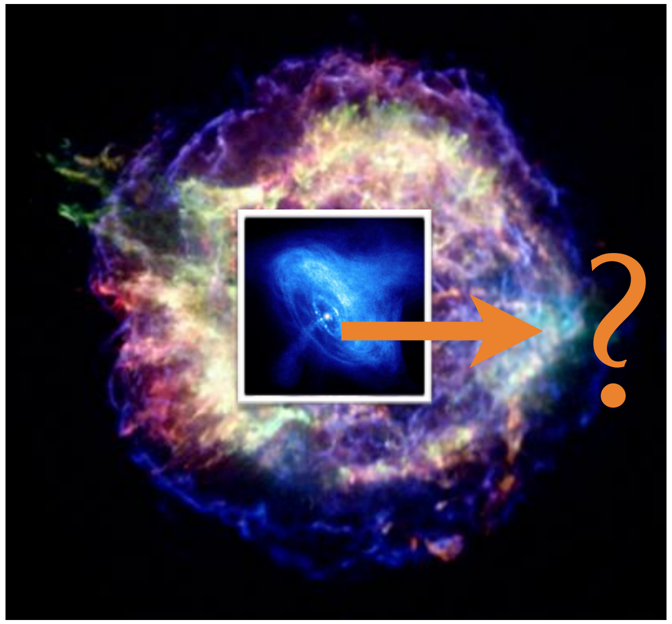


$$\frac{\mathrm{d}N_\mathrm{i}}{\mathrm{d}E} = \frac{9}{2}\frac{c^2 I}{Z e B_* R_*^3 E}\left(1 + \frac{E}{E_\mathrm{g}}\right)^{-1}$$

hard injection spectrum:
-1 slope

supernova envelope: do accelerated particles survive?

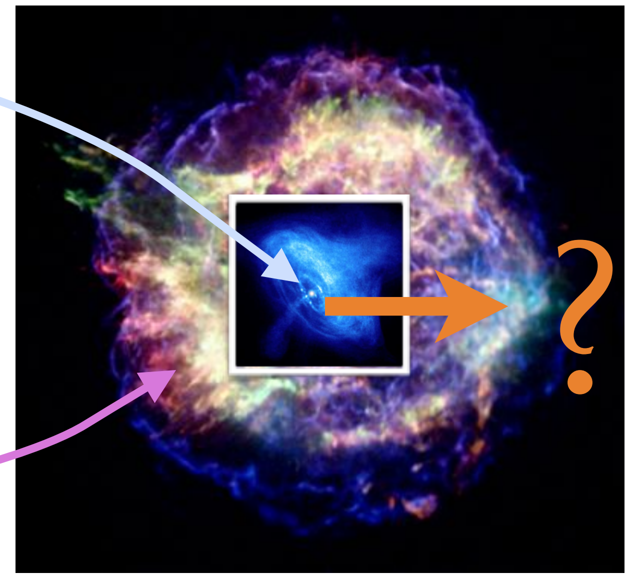
SN envelope = dense baryonic background
UHECR experience hadronic interactions



Fang, KK, Olinto 2012

pulsar
magnetic moment μ,
rotation velocity Ω,
particle acceleration rate η

supernova
ejecta energy E_{ej},
ejected mass M_{ej},



- Analytical estimates
- Monte-Carlo propagation, hadronic interactions with EPOS + CONEX

tight for protons

(would work for very dilute SN envelopes)

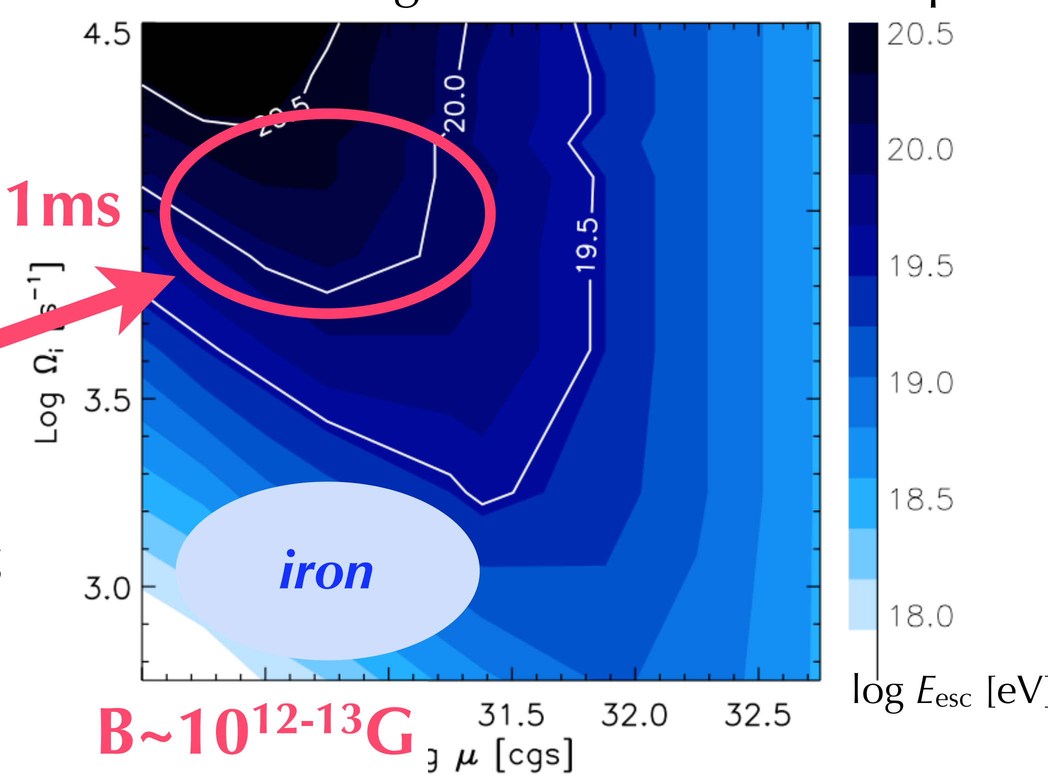
= 10 M_{sun}
= 10^{51} erg

our successful accelerator:
millisecond pulsar
in standard core-collapse SN

birth rate needed: 0.01% of total 'normal' extrag. pulsar rate (10^{-4} Mpc^{-3} yr^{-1})

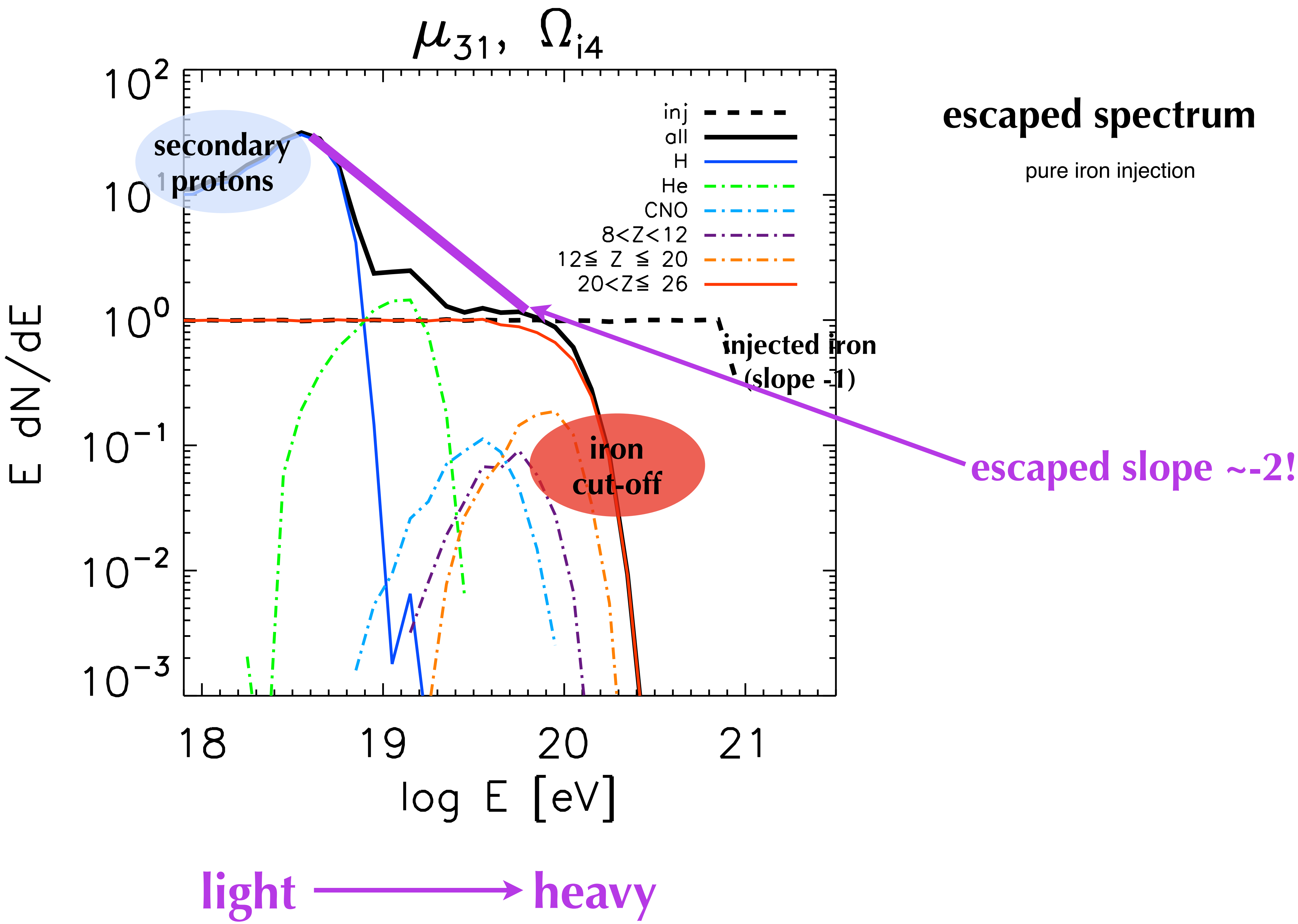
OK for iron:

accelerated to Z x higher E when SN envelope dilute



Collateral good news: spectrum, composition!

Fang, KK, Olinto 2012

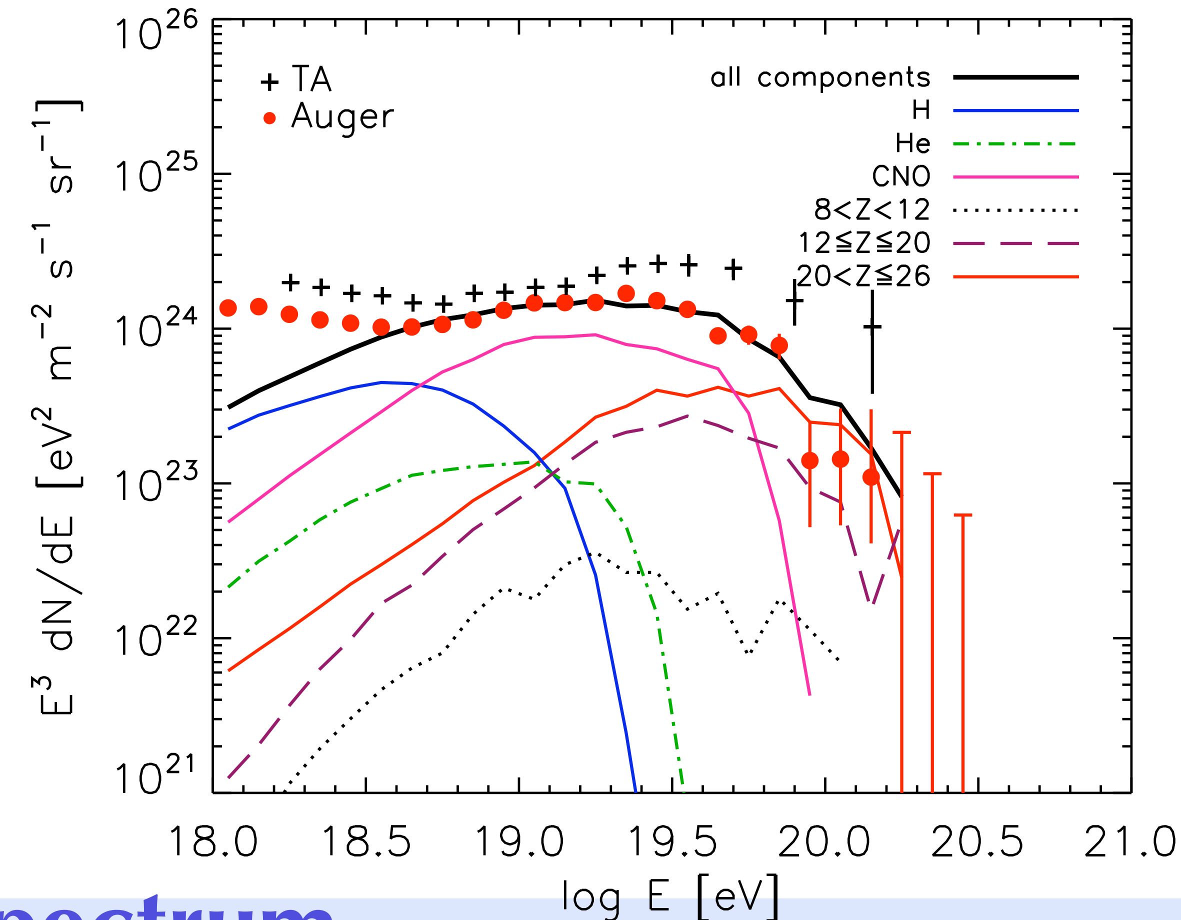


escaped spectrum

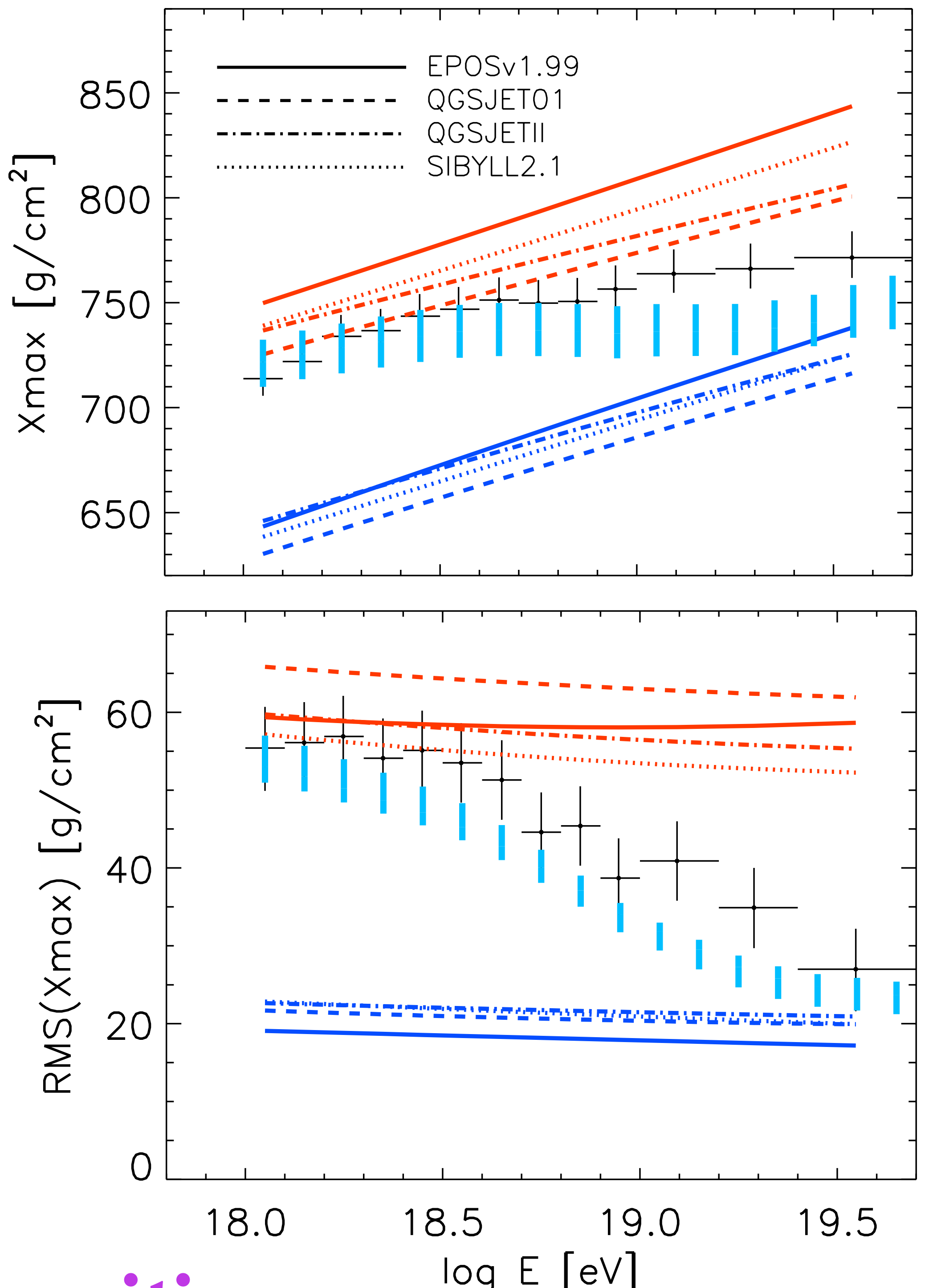
pure iron injection

A scenario that fits UHECR Auger data (rare)

Fang, KK, Olinto 2012
Fang, KK, Olinto, in prep.



spectrum



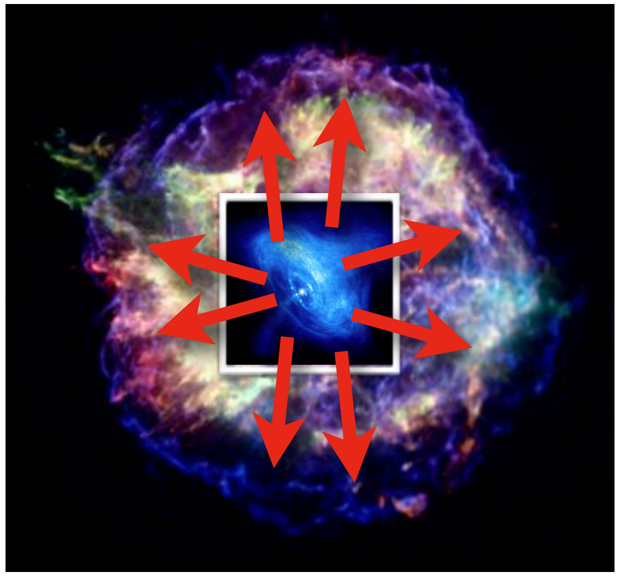
composition

propagated 75%p, 20%CNO, 5%Fe @injection

A signature in the supernova lightcurves

KK, Phinney, Olinto in prep.

pulsar millisecond with B~10^{13}G

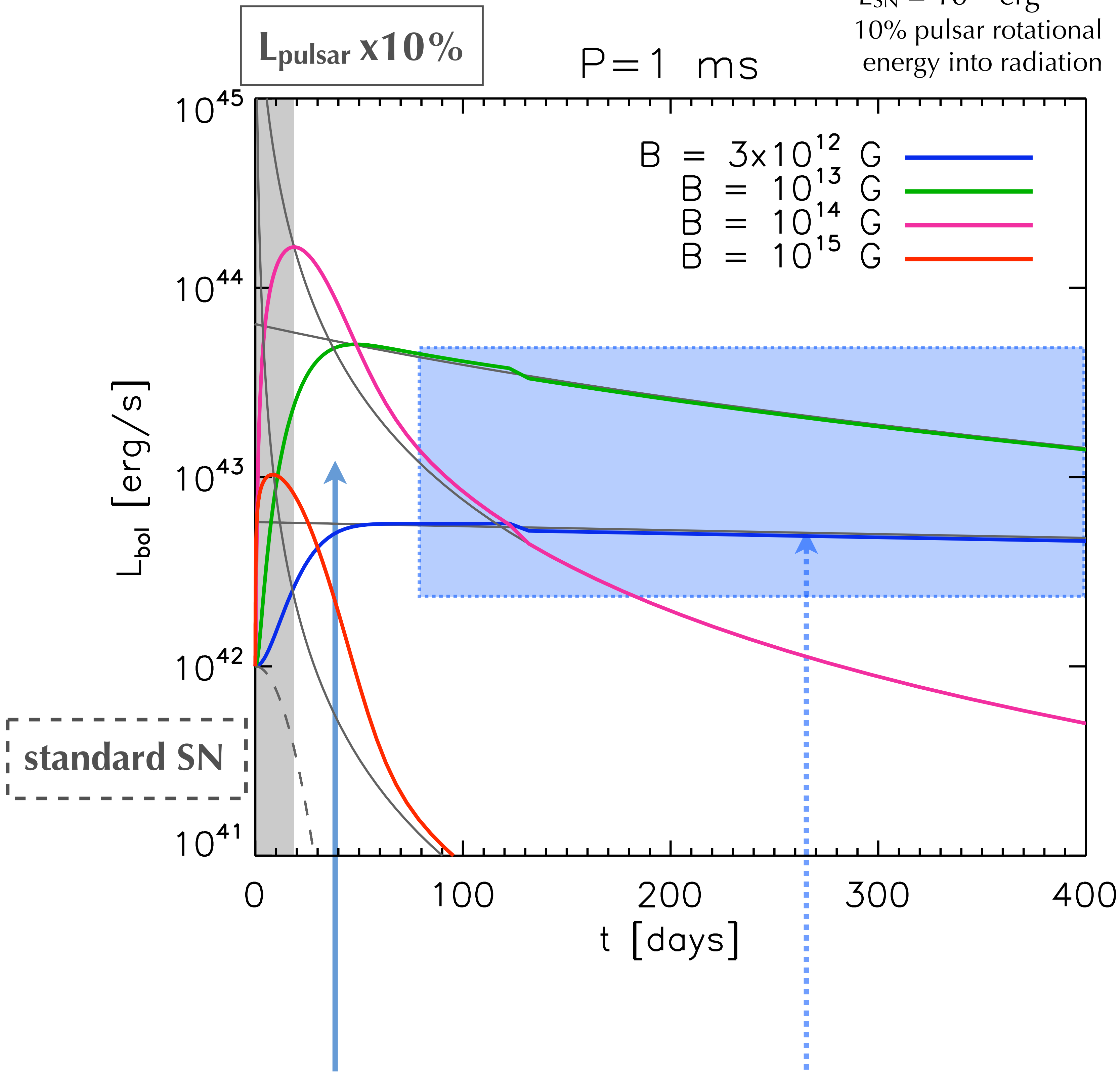


injection of
LARGE
pulsar rotational energy
into SN ejecta
E~10^{52} erg

↓

change radiation emission
from SN

$M_{ej} = 5\ M_{sun}$
$E_{SN} = 10^{51}$ erg
10% pulsar rotational energy into radiation

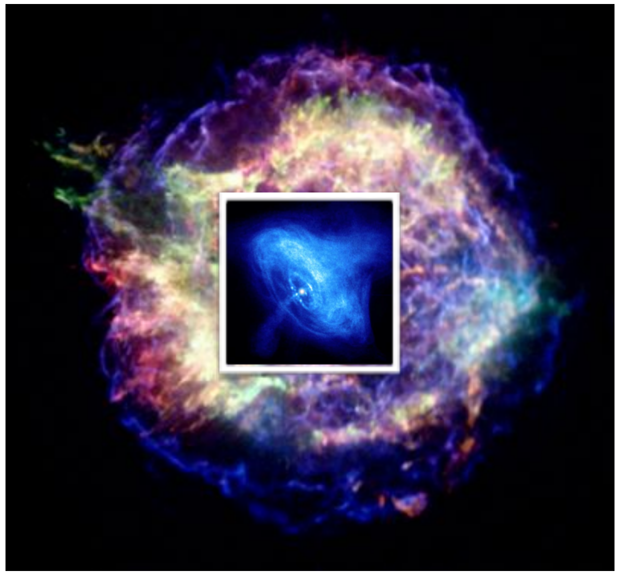


- possibly ultraluminous
- interesting lightcurve @ few years

high plateau (in bol.)

Peculiar supernova lightcurves

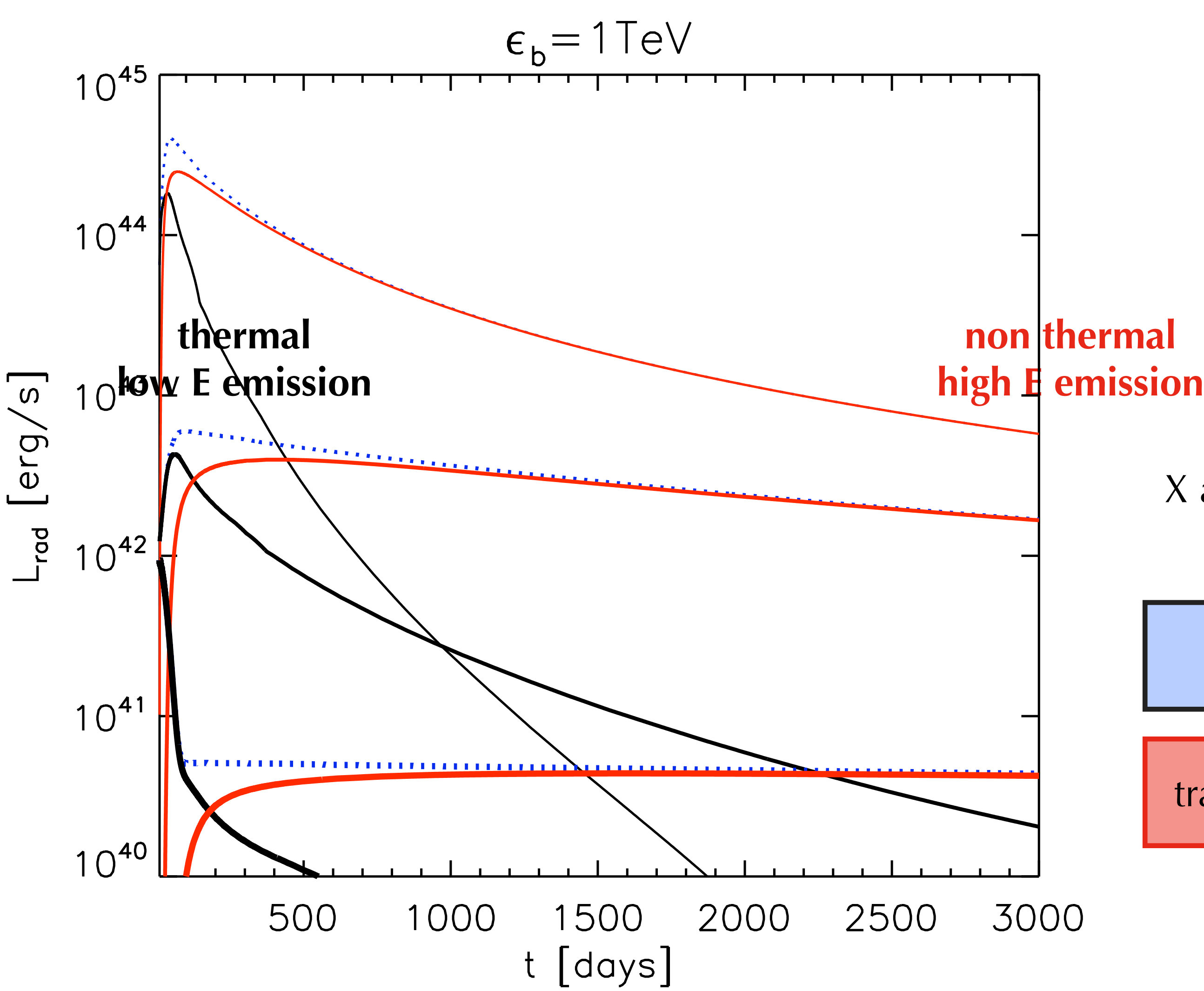
KK, Phinney, Olinto in prep.



$M_{ej} = 5\ M_{sun}$
$E_{SN} = 10^{51}$ erg

10% pulsar rotational energy into radiation

Follow up of SN lightcurves over **a few years** in **all wavelengths** will be crucial



X and gamma ray injection from pulsar wind nebula

SN ejecta opaque to X,gamma rays --> thermalization

transparent : X ray emission

What will be needed to find the sources of UHECRs

UHECR data:

more statistics for anisotropy signatures (transient/steady sources)
more statistics for shape of energy spectrum at highest E
more statistics for chemical composition at highest E

JEM-EUSO

Particle Physics:

shower development, parameters for hadronic interactions

Astrophysics:

better understanding of most powerful sources: escape issues
measurements of intergalactic magnetic fields

multi-wavelength studies from radio to gamma-rays

measurement of gamma-ray halos? (e.g. Neronov & Semikoz 09)

LOFAR, SKA

Other messengers:

cosmogenic neutrinos (produced during propagation)
gamma-rays (GeV to UHE)
gravitational waves *KK 2011*

KK, Allard & Olinto 2010
KK, Allard & Lemoine 2011

could be observed for reasonable source scenarios if composition is dominated by protons

Surprisingly promising candidate: millisecond pulsars

signatures if birth in our Local Group
look for signatures in SN light curves @ few years after explosion

Fang, KK, Olinto 2012
Fang, KK, Olinto in prep.
KK, Phinney, Olinto in prep.